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Simulation and Optimization of Silicon Solar Cell Using MgF_2/SiO_2 Double - Layer Anti – Reflective Coating (ARC)

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ABSTRACT

The most common method of harnessing solar energy is photovoltaic. With the revolution of new energy innovation in recent years, generation of electricity based on photovoltaic has possessed great progress, however, high cost is one of the primary issues encountered. In order to drive into a better manufacturing technology, the effectiveness of the cells and modules is opt for further cost reduction. The purpose of this research is to study the parameter on crystalline silicon solar cell with double layer of MgF_2/SiO_2 as its anti-reflective coating (ARC) which is the thickness. An antireflection coating mostly introduced in solar cell in order to reduce the reflection of light from the front surface of the cell and to enhance broadband of light absorption. Four Light trapping (LT) scheme with double layer of MgF_2/SiO_2 and adjusted thickness on 100 µm thin crystalline silicon(c-Si) was investigated. The optical properties within 300-1200 nm wavelength region were analyzed and from absorption curve, maximum potential photocurrent density (J_{max}) for each LT schemes was calculated. With the addition of ARC into the c-Si, the J_{max} increased up to 32.13 mA/cm^2 and achieved 28.89 % enhancement compared to the J_{max} of the c-Si reference (without ARC). Therefore, it is important to achieve optimum value in absorption that literally showed the excellent optical property of MgF_2/SiO_2 bilayer coatings.

Keywords: Solar cell; MgF_2/SiO_2; Anti-reflection coating (ARC); Potential Photocurrent Density.

INTRODUCTION

Photovoltaic modules have a reduced conversion efficiency even before the solar cell receives light [1]. Light is reflected at the interface between the module and the air when the module is lit, limiting the amount of light absorbed by the solar cell. Most solar cells utilize a thin of dielectric layer, in other words known for anti-reflective coating to decrease light reflection from the cell's front surface. Anti-reflective coatings are composed of a small layer from dielectric material with a specified thickness along with refractive index that generates interference effects. The absorption of incident photon was somehow enhanced, and thus the photo-generated current, which does have a profound impact on the efficiency of solar cell. Light absorption in silicon solar cells rises across the whole wavelength range based on the sheer enhance light absorption cause by ARC [1]. As a result, antireflection coating (ARC) is important for increasing solar cell conversion efficiency. However, due to refractive index limitations, there are only a few anti-reflective coatings compounds available. Anti-reflective coatings have been demonstrated in a range of materials including SiO_2, Si_3N_4, ZnO, ZnS, ITO, TiO_2, MgF_2/ZnS and others although their effectiveness is highly reliant on the anti-reflective coating design and solar cell application [2-4].

Due to their high performance of conversion and long-term stability in a variety of environmental situations, good efficiency of crystalline silicon solar cells is the frequently used solar cells in the industry [5]. A good blend of antireflection coatings is required to generate a high-efficiency solar cell as it reduces optical reflections and increases light transmission over a wide range of wavelengths [6]. Choosing the right material combinations for antireflection coatings is difficult especially when working with many layers. MgF_2/SiO_2 bilayer coatings was chosen due to its nanoporous structure with low refractive index that allows researchers to easily design ARC with a broad band [7].

Planar surface of crystalline silicone (c-Si) was used as reference or main body. A 50 nm thick MgF_2 ARC with refractive index, n = 1.38

was added on the top of c-Si as the bottom layer and SiO_2 added as the top layer. The absorption wavelength will be about 300 – 1200 nm where in this region, the MgF_2/SiO_2 bilayer coatings yielded an excellent optical property. At zero incident angle which is applicable to the surface of solar cell, the standard AM1.5G solar spectrum of sunlight was employed [8]. The optical properties within 300-1200 nm wavelength region were analysed using wafer ray tracing simulation and from the absorption data, maximum potential photocurrent density (J_{max}) for each LT schemes was calculated.

METHODOLOGY

For the anti-reflective coating, Sun *et al.* [7] proposes MgF_2 as the bottom layer and SiO_2 as the top layer. Thus, for the thickness, the bottom layer or MgF_2 was maintained with constant thickness that would be 50 nm and its refractive index (n = 1.38) while the top layer or SiO_2's thickness was fixed at 50, 70, 90, and 110 nm. The variables were maintained with one layer to avoid systematic error that gives insufficient result in absorption. So, to illustrate the layer materials, imagine house and its roof where the house (substrate) is the body reference is c-Si. Meanwhile, the roof (front film) is double layer MgF_2/ SiO_2. Apart from that, the AM1.5 global solar spectrum was selected since it is suitable for flat panel modules and has an integrated power of 1000 W/m^2 (100 mW/cm^2). The AM1.5 Direct (+circumsolar) spectrum was developed for solar concentrator work [8]. The type of ARC used in this research was planar surface with double layer ARC of MgF_2/ SiO_2. By using planar as the front surface makes it easier as it focuses only the ARC. Additionally, optical properties of the solar cells were investigated at 300 -1200 nm region wavelength [9].

MgF_2/SiO_2 Model Scheme

Figure 1 shows schematic diagram of light trapping (LT) schemes in thin crystalline silicone c-Si (with 100 µm thickness) for solar cell. Figure 1 (a) is a Reference c-Si with (no LT scheme) while Figure 1 (b) shows the schematic diagram of c-Si combined with double layer anti-reflective coating of MgF_2/SiO_2 where refractive index for MgF_2 (n = 1.38). Figure 2 shows scheme I-1V, with a constant 50 nm thick MgF_2 ARC (refractive index, n = 1.38) was added on the top of c-Si as the bottom layer and SiO_2 was added as the top layer. Only thickness parameter of SiO_2 was adjusted to gain maximum absorption of light.

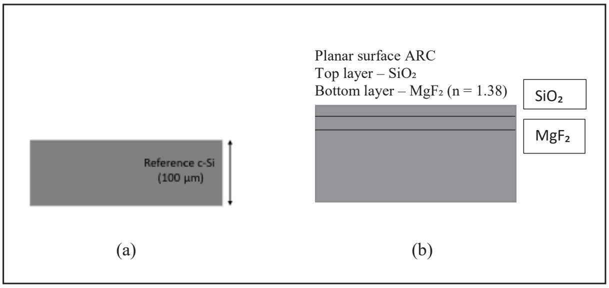
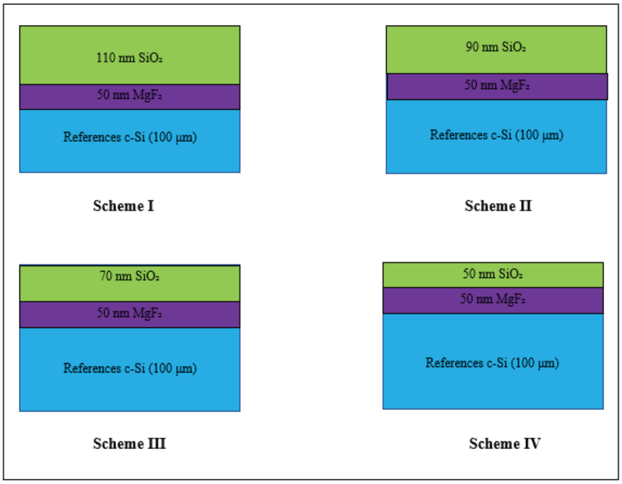


Figure 1: Schematic diagram thin c-Si (with 100 µm thickness) for Solar Cell a) References c-Si (no LT scheme) b) c-Si Solar Cell (with LT Scheme).



*Scheme (I): MgF_2 ARC with a constant thickness of 50 nm while SiO_2 ARC thickness of 110 nm).

Scheme (II): MgF_2 ARC with a constant thickness of 50 nm while SiO_2 ARC thickness of 90 nm).

Scheme (III): MgF_2 ARC with a constant thickness of 50 nm while SiO_2 ARC thickness of 70 nm).

Scheme (IV): MgF_2 ARC with a constant thickness of 50 nm while SiO_2 ARC thickness of 50 nm).

Figure 2: Schematic diagram of double layer ARC on Substrate Silicon.

Calculation of The J_{max}

Total reflection, transmission and absorption in thin c-Si wafers, parasitic absorption in ARC including J_{max} are all investigated and analyzed by using incremental LT schemes. LT was developed as a result of absorption investigations in thin c-Si. J_{max} is a metric used to assess the performance of a c-Si solar cell. By integrating the J_{max}, J_{max} is finally obtained. Absorption curve for wavelength of 300-1200 nm in the AM1.5G solar spectrum was used in order to find J_{max} [9,10]. The AM1.5 Direct (+circumsolar) spectrum was developed for solar concentrator work and equation (1) shows the calculation of J_{max},

$$J_{\max} = q \int EQE(\lambda).S(\lambda) \tag{1}$$

In the AM1.5G spectrum, the electron charge is q and for the usual spectral photon density of sunlight is S (λ). Carrier collection is assumed to be one in this calculation (internal quantum efficiency, IQE=1).

J_{max} Enhancement

J_{max} enhancement was calculated as shown in Equation (2).

$$J_{\max}\text{ enhancement} = [(J_{\max}\text{ LT scheme} - J_{\max}\text{ ref})/J_{\max}\text{ref}] \text{ x } 100 \tag{2}$$

Wafer Ray Tracer Simulation

Figure 3: Online simulation Wafer Ray Tracer by PV Lighthouse.

Simulation in Figure 3 functioned as medium to achieve the curves for absorption, reflection and transmission (RAT) through key in those parameter value according to the study. The RAT data then can be exported and used to gain value of J_{max}.

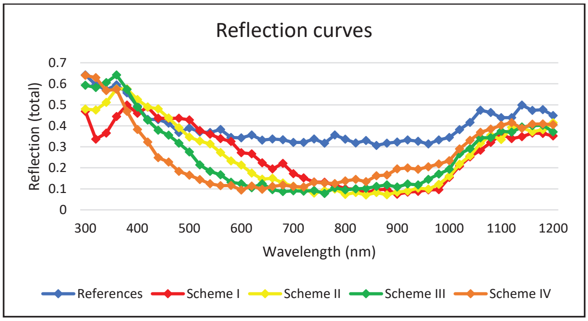
As discussed in the previous section, RAT data that has been exported was later converted into CSV file and run through simulation. Next, the result appeared in the form of graph and tabular of data. From the data, it was possible to know the value of Jmax for each LT schemes. In order to attain great absorption, J_{max} enhancement percentage measured should be increased from time to time alongside with the J_{max} until they reach their maximum.

RESULTS AND DISCUSSION

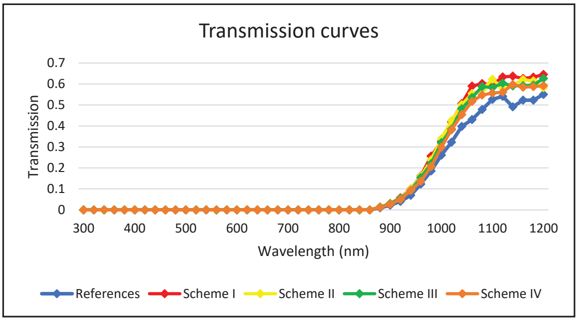
Effect of ARC Parameters towards Reflection, Absorption and Transmission Curves

For comparison purposes, the reference c-Si curves are provided in Figure 4(a-c). It exhibits significant reflection over the wavelength in the range of 300-1200 nm. In Figure 4a, at 600 nm wavelength, the reflection for the reference was about 35 %. Meanwhile, the difference between the reference and other schemes are nearly 25 %. This can be due to its refractive index of incoming light rapidly changes as it moves and strikes through c-Si reference body with 3.5 of refractive index from air n=1.0 [11]. In Figure 4b, for wavelength of 940 nm and above, transmission for reference was lower compared to other four schemes and at 1080 nm it reaches about 52 %. Because of c-Si's narrow inability, long wavelength light cannot be absorbed and even strikes in a single pass. In Figure 4c, the standard reference of c-Si has such a low broadband of absorption where it only can increase to 63 % at 700 nm since it does not pair up with any kind of LT schemes. This is one of the important purposes to confirm on why efficient LT systems are needed in thin c-Si solar cells. Continuous adjustment of the thickness for both layers are the only way to find out which is the best to achieve high value in absorption. Trial and error for several times by thickening or narrowing the thickness until absorption curves reaches its optimum was done.

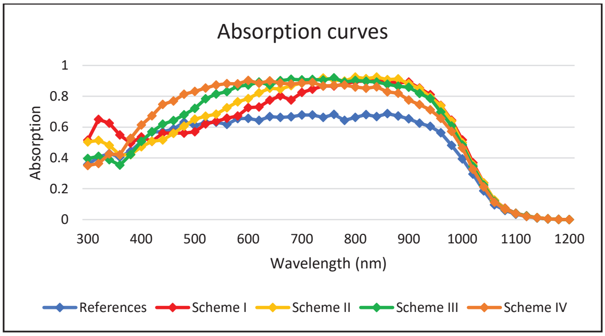
In this research, ACR for bottom layer, MgF_2 was kept constant at 50 nm and the thickness for top layer, SiO_2 was changed. During the simulation, literally found out that in range between 50 – 110 nm SiO_2 thickness, it gives high absorption. If both layers have high values of reflective coatings, it will boost surface reflectance and increases the reflection curves. So, in this case, by narrowing the coating thickness, it will reduce the reflection and enhance the absorption. With Scheme I, planar with double MgF_2/SiO_2 ARC (MgF_2 = 50 nm, SiO_2 = 110 nm), it results in increased light scattering at the air-planar surface. The comparison for this Scheme I together with reference of c-Si shows that reflection from 600 to 1000 nm was lower. Reflection reduced to 10 % at 900 nm wavelength in Figure 4a. The transmission of long wavelength light was 64 % at 1100 nm. Broadband light absorption risen sharply as light scattering rises. 90 % of absorption curves increased at a wavelength of 850 nm as depicts in Figure 4c.



(a)



(b)



(c)

Figure 4: (a) Reflection (b) transmission and (c) absorption curves for thin c-Si (100 µm thickness) with incremental LT schemes. Reference c-Si is included for comparison.

From Figure 4a, Scheme II (MgF_2 = 50 nm, SiO_2 = 90 nm) reduces reflection from 750 to 900 nm or even further compared to Scheme I. This was expected given that the ARC has a quarter wavelength coating effect which is designed to reduce broadband reflection and enhance light coupling into the thin c-Si [12]. The lessen rear reflection offers a double-pass and resulted in randomized long wavelength light at the rear end of the thin c-Si absorber [13]. In Figure 4b, at 1100 nm, the transmission of the high wavelength is mild and 62 % higher than the reference. Broadband mild absorption may rise substantially as mild scattering continues to improve. At a wavelength of 800 nm, absorption expands to reach 95 % as in Figure 4c.

Reflection for Scheme III (MgF_2 = 50 nm, SiO_2 = 70 nm) was similar to Scheme II, where reflection dropped to 10 % at 700 nm to 900 nm wavelength region, as shown in Figure 4a. Furthermore, for Scheme III in Figure 4b, the transmission curve only has 3 % of difference compared to Scheme II where the transmission occurs approximately at 59 %. Same goes to the absorption, the curves most likely identical to surpass 95 % at 800 nm just as in Scheme II in Figure 4c.

As for Scheme IV (MgF_2 = 50 nm, SiO_2 = 50 nm), the reflection reduced to 10 % when wavelength reaches 600 nm and this value was maintained until 750 nm. This was due to the increased light scattering on the planar-air interface. In Figure 4b, the transmission was 0 % until 900 nm and increased to 54 % at 1050 nm. For absorption, more than 90 % was achieved at wavelength of 600 nm as shown in Figure 4c.

Effect of ARC Parameters towards Optical Pathlength Enhancement

Figure 5 shows the optical pathlength of incident light at thin c-Si through using incremental LT scheme. The reference of c-Si together with other schemes show Z = 1 over the entire wavelength range from 300 to 880 nm shows a simple transmission of incident light through a thin c-Si absorber. As an outcome, Z increased to between 1.2 and 1.4 in length at a wavelength of 1000 nm and an increment in wideband absorption was observed. Only when all schemes including reference were accepted, Z appeared the same. This observation was predicted since the front planar ARC obtained better optical coupling to thin c-Si without adding new scattering of incident light. Thus, there is no significant difference in optical pathlength growth (Z). This is due to the double ARC which reflects long wavelength light back to thin c-Si and absorbs it [14]. Consequently, c-Si's long wave absorption was enhanced.

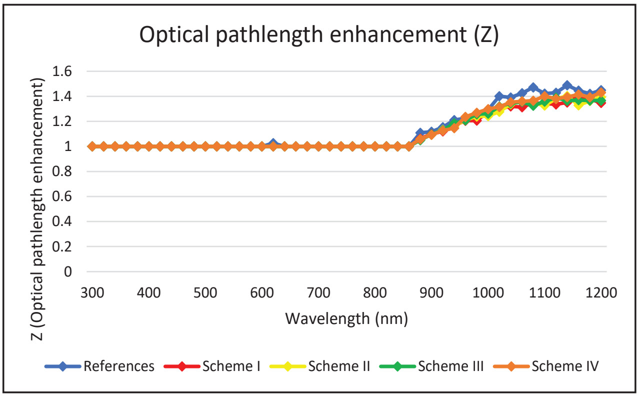


Figure 5: Optical pathlength enhancement (Z) in thin c-Si (with 100 μm thickness) against wavelength (nm) with incremental LT schemes. Reference c-Si is included for comparison.

J_{max} Performance Measurement

Table 1 presents the J_{max} measured value of the thin c-Si (with 100 μm thickness) with incremental LT schemes. Then, percentage of J_{max} enhancement was calculated with the aid of using normalizing the J_{max} for every LT scheme in online simulation (simulation to calculate Jsc from EQE) finally to the J_{max} of the reference c-Si which without LT scheme.

From Scheme I (110 nm), in comparison with the reference of c-Si where J_{max} equals to 24.93 mA/cm^2. J_{max} raised to 29.67 mA/cm^2 that signifies 19.01 % of enhancement. Apart from that, because of the increased light coupling via the ARC, light absorption within the thin c-Si start to boost at some stage in the complete wavelength place using Scheme II (90 nm). J_{max} increased to 30.85 mA/cm^2 which showed 23.75 % improvement. Once Scheme III (70 nm) was employed, high optical light absorption in the thin c-Si increased. The J_{max} tends to increase for about 27.96 % enhancement at 31.90 mA/cm^2. Last but not least, for Scheme IV (50 nm), high optical wavelength for absorption of light finally gained about 32.13 mA/cm^2 with 28.89 % enhancement.

Table 1: Summary of J_{max} of thin c-Si (with 100 μm thickness) with incremental LT schemes. J_{max} of reference c-Si is included for comparison.

LT Scheme	J_{max} (mA/cm^2)	J_{max} enhancement (%)
Reference c-Si (thickness = 100 μm)	24.93	-
Scheme I: Planar with double MgF_2/SiO_2 ARC (MgF_2 = 50 nm, SiO_2 = 110 nm)	29.67	19.01
Scheme II: Planar with double MgF_2/SiO_2 ARC (MgF_2 = 50 nm, SiO_2 = 90 nm)	30.85	23.75
Scheme III: Planar with double MgF_2/SiO_2 ARC (MgF_2 = 50 nm, SiO_2 = 70 nm)	31.90	27.96
Scheme IV: Planar with double MgF_2/SiO_2 ARC (MgF_2 = 50 nm, SiO_2 = 50 nm)	32.13	28.89

CONCLUSION

In this work, ray tracing of LT schemes in thin c-Si of solar cells with 100 µm thickness has been investigated. MgF_2/SiO_2 was applied for bilayer ARC. There were four LT schemes which was investigated, that would be from multiples values of SiO_2 thickness (110, 90, 70 and 50 nm). This study shows that bilayer anti-reflective coating with 50 nm thickness of SiO_2 was the most effective among others LT schemes leading to 28.89 % enhancement. This signifies that the absorption of incident photon was somehow enhanced and thus the photo-generated current, which does have a great impact on the efficiency of solar cell. To increase light absorption, the optical losses in the c-Si which were contributed by reflection in the short and long wavelength region need to be suppressed.

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