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Comparison of nano-structured solar cell anti-reflection coating based on graded-index or mode coupling approach

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Abstract

Solar cell nano-structured anti-reflection coatings based on graded index (GI) and mode coupling are all proposed to significantly reduce the reflection from semiconductor–air interface. In this work, it is shown that purely graded index approach can lead to degradation of long wavelength absorption by eliminating quasi-guided mode excitation. The reason is that the physically graded layer not only provides low reflectance path from air to semiconductor, but also from semiconductor to air, leading to photon escape. This results in out-coupling of photons from the semiconductor to air. On the other hand, anti-reflection coating based on mode coupling does not suffer from degraded long wavelength absorption and it is capable of acting as one-way photon pass coating. It is found that the sidewall thickness of mode coupling anti-reflection coating has significant impact on its effectiveness for anti-reflection, and therefore the selection of process methods is critical for its low reflectance. It is proposed that the purely graded index coating is more suitable for wafer-based photovoltaics where full absorption is possible by two photon traces. The mode coupling coating is suitable for both wafer-based photovoltaics and thin-film photovoltaics since it provides not only low reflectance but also long wavelength quasi-guided mode excitations. In the end, new types of anti-reflection coating and light trapping structure are proposed to further enhance the performance.

Keywords: Anti-reflection coating; Solar cell; Graded index; Mode coupling

1. Introduction

Photonic nano-structures have been emerging as promising candidates for anti-reflection (ARC) coatings. Specifically for solar cells, broadband low reflectance is the basic requirement for effective ARC to accommodate the broad solar spectrum. Several schemes are proposed, among which the most effective one shows decent broadband characteristics is so-called graded index (GI) approach. Anti-reflection coatings falling into this category includes dielectric multi-layer structures [1], semiconductor nano-tips [2], and closely related dielectric nano-structures [3,4] which can actually be regarded as a pseudo-graded index approach. In this work, it is going to show that while purely graded-index approach can provide broad-band low-reflectance characteristic, it can significantly degrade long wavelength waveguiding. This is because the low reflectance is based on physically graded index and, therefore, the low reflectance nature exists for both air to semiconductor and semiconductor to air incidence. Since photons can easily go through the graded index layer from semiconductor to air, they can

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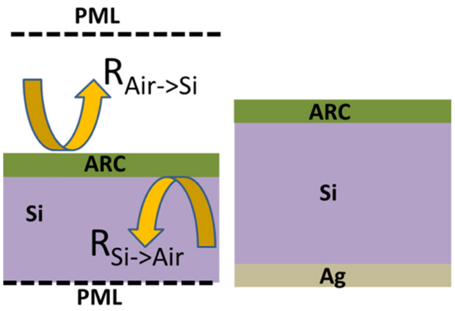

Fig. 1. The simulation structure for (left) the anti-reflection coating reflectance and (right) the solar cell absorbance.

easily escape the device leading to degraded long wavelength light trapping. Another category of anti-reflection coating does not count on physically graded material layers and instead it utilizes the mode coupling through the periodic grating structures on the solar cell front surface. This category includes ZnO nanorods [5], surface plasmon ARCs [6–9], grating couplers [10], and the recently proposed, very promising dielectric ARC based on Mie scattering [11]. It is shown here that ARC based on mode coupling is more robust to long wavelength absorbance degradation because the mode coupling ARC does not provide low reflectance path for photons coming from semiconductor to air. Therefore, it provides one-way photon pass, compared to the significant photon outcoupling resulted from the graded index ARC.

2. Geometry and simulation details

In this study the reflectance and absorbance are calculated for silicon solar cells with various nano-structured ARCs. The structure for absorbance calculation is ARC + 0.3 μmSi + Ag, while the structure for reflectance calculation is ARC + Si + perfectly matched layer (PML). It is a common practice to include only the front surface texture when comparing the effectiveness of anti-reflection characteristics [1–3,11].

The study of photon in- and out-coupling is done by calculating the reflectance from air through ARC to Si, and the reversed reflectance from Si through ARC to air, as illustrated in Fig. 1. When calculating the reversed reflectance, the imaginary part of silicon dielectric constant is neglected due to the constraint that the source region cannot be lossy. This practice has been employed in the literature [12]. In fact, the purpose of this work is studying the degradation of long wavelength guided modes, and the imaginary parts of dielectric constant at long wavelength are generally not very significant due to weak material absorption. It is going to show later that one-way photon pass is the key for anti-reflection coatings to have both low reflectance from air to semiconductor and strong quasi-guided modes at long wavelength to maintain solar cell light trapping.

In most of the solar cell technologies including wafer-based photovoltaics and multi-junction solar cells, the metal contact will be deposited through the vias in the insulating ARCs. In the case where transparent conducting contacts are needed, the ARCs materials presented in this paper can be replaced by transparent conducting oxide (TCO) such as indium tin oxide (ITO), aluminum doped zinc oxide (AZO), fluorine-doped tin oxide (FTO). Nevertheless, it should be pointed out that the comparison presented in this work, i.e., difference between graded index ARCs and mode coupling ARCs, will not change.

In this work, the choice of materials, i.e., SiO_2 TiO_2 Si_3N_4, is to align with the literature [1–3,11]. For wafer-based or multi-junction photovoltaics, insulators are frequently used as ARCs and the reflectance is more important since photons can be absorbed in one or two photon passes. For thin-film photovoltaics, TCOs are frequently used as ARCs and the absorbance is more important since the photons cannot be absorbed fully within two photon passes. In order to have a unified material selection and fair comparison, same ARC materials are used for both absorbance and reflectance calculations. Nevertheless, changing ARCs to other materials instead of what is used in this work will not change the key observation and conclusion presented here.

The absorbance is calculated by integrating the power dissipation in silicon:

$$A(\lambda) = \frac{1/2 \int_V \omega\varepsilon_0\varepsilon''(\lambda)|\vec{E}(\vec{r})|^2 dv}{1/2 \int_S Re\{\vec{E}(\vec{r}) \times \vec{H}^*(\vec{r})\} \cdot d\vec{s}} \tag{1}$$

where ω is the angular frequency, λ is the free space wavelength, ε_0 is the permittivity in vacuum, and ε'' is the imaginary part of complex semiconductor dielectric constant. The normalized integrated absorbance can be defined to compare different ARCs. This is needed since the active silicon material volume might be different for various ARCs.

$$A_{Int} = \frac{V_{Si,Ref}}{V_{Si}} \frac{\int \frac{\lambda}{hc}\Omega(\lambda)A(\lambda)d\lambda}{\int \frac{\lambda}{hc}\Omega(\lambda)d\lambda} \tag{2}$$

where $V_{Si,Ref}$ is the silicon volume of one period (P) for the planar cell. In this study the silicon thickness is taken to be 0.3 μm and thus $V_{Si,Ref} = P \times P \times 0.3$ μm. V_{Si} is the silicon volume of one period for the solar cell structure with a specific front surface coating. $\Omega(\lambda)$ is the AM 1.5 solar spectrum in unit of $J\,s^{-1}\,cm^{-2}\,nm^{-1}$,