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Optimization of the antireflection coating of thin epitaxial crystalline silicon solar cells

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Abstract

In this work we use an effective weighting function to include the internal quantum efficiency (IQE) and the effective thickness, T_e, of the active cell layer in the optical modeling of the antireflection coating (ARC) of very thin crystalline silicon solar cells. The spectrum transmitted through the ARC is hence optimized for efficient use in the given cell structure and the solar cell performance can be improved. For a 2-µm thick crystalline silicon heterojunction solar cell the optimal thickness of the Indium Tin Oxide (ITO) ARC is reduced by ~8 nm when IQE data and effective thickness are taken into account compared to the standard ARC optimization, using the AM1.5 spectrum only. The reduced ARC thickness will shift the reflectance minima towards shorter wavelengths and hence better match the absorption of very thin cells, where the short wavelength range of the spectrum is relatively more important than the long, weakly absorbed wavelengths. For this cell, we find that the optimal thickness of the ITO starts at 63 nm for very thin (1 µm) active Si layer and then increase with increasing T_e until it saturates at 71 nm for $T_e > 30$ µm.

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Keywords: antireflection coating; epitaxial silicon solar cell

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1. Introduction

Reduction of the wafer thickness has so far been a significant factor driving cost reduction in silicon-based solar cells. However, moving beyond 100-µm will likely impose significant challenges related to handling [1] in addition to the relative increase in kerf losses [2]. Epitaxial silicon growth and layer transfer techniques provide ways to continue the trend of reduced silicon usage. Naturally, silicon provides the perfect seed for epitaxial growth, and various lift off techniques have been studied in order to reuse the expensive silicon substrate. Another approach is to use a low-cost substrate, such as display glass or metal foil, which remains attached to the solar cell. The realization of high quality crystalline silicon on such substrates requires a carefully chosen seed-layer for epitaxial growth. In this work we focus on tailoring the antireflective properties of the ARC to match the cell structure of an ultrathin, heterojunction, epitaxial crystalline silicon solar cell. A schematic view of the crystalline silicon heterojunction cell is shown in Figure 1. A variety of homo- and heteroepitaxial seeds on glass substrates [3,4] have been investigated, but for this particular study an n^+ Si wafer was used as the substrate for the epitaxial growth. For the thin heterojunction solar cells, the conductance in the doped a-Si:H layers is not high enough to allow for an efficient lateral collection. Transparent conductive oxides (TCOs) are often used to address this issue. The TCOs must also have a high transmittance in order to provide light to the active layer of the cell. As typical TCOs have refractive indices $n \approx 2$, such layers can also function as an anti-reflection coating for the solar cells.

For all crystalline Si thin film approaches, the combination of crystalline material and very thin active layers make light trapping a prerequisite to increase the current density. The aim of all light trapping approaches is to increase the average path length of the incoming photons. A 1-µm thick silicon layer with front side texture and rear reflector may therefore absorb the same amount of light as a flat 10-µm layer. It is therefore convenient to use the effective Si thickness, T_e, to account for arbitrary light trapping structures.

Efficient antireflection coatings (ARCs) are important to improve the light collection properties of solar cells of all thicknesses. Single layer ARCs for thick absorbers are well known and their only purpose is to reduce reflections without absorbing light in the ARC itself. Such ARCs are simply optimized for minimal integrated reflectance with respect to the AM1.5 spectrum. However, for very thin silicon solar cells, the cell thickness and structure will affect the properties of the optimal ARC to a larger extent. Although the improvement in current density after application of specific ARCs are commonly reported [6, 7], this does not implicate that the ARC is optimized with respect to the current density or cell structure. Modeling of the optical properties is predominantly performed using special purpose software and is hence normally separated from the electrical and structural modeling of the solar cell. In this work we use an effective weighting function to include the internal quantum efficiency (IQE) and the effective thickness of the active cell layer in the optical modeling. The spectrum transmitted through the ARC is hence optimized for efficient use in the given cell structure and the solar cell performance can be improved.

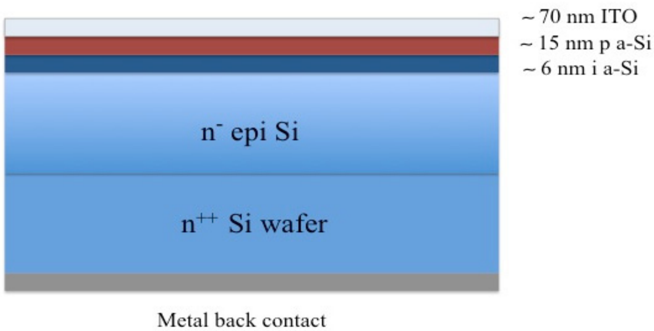

Fig. 1. The structure of the epitaxial crystalline silicon cell

2. Experimental method

The epitaxial film is grown on the n^+ substrate in a hot wire chemical vapor deposition (HWCVD) chamber. Details of the epitaxial growth of the heterojunction device is described elsewhere [8]. The heterojunction emitter is composed of 6 nm intrinsic a-Si:H and 15 nm p-type a-Si:H deposited using HWCVD. The 70 nm thick ITO (In_2O_3:Sn) layer is deposited by reactive evaporation of an In/Sn compound.

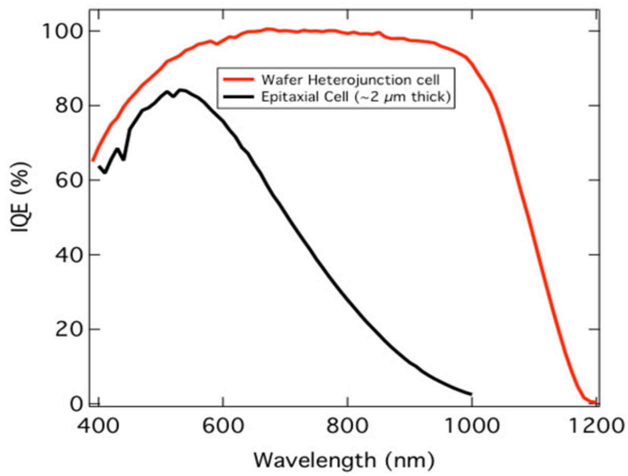

Fig. 2. IQE data for a thin epitaxial cell and for an optically thick wafer cell.

The IQE data, shown in Fig. 2, were taken on an Oriel IQE 200 system in the range 400-1000 nm. The IQE values are derived from the reference cell and are kept constant during the simulations. Note that the low IQE from approximately 600 nm and further into the infrared is mainly due to absorption in the n^{++} seed wafer. The thick n^{++} wafer should be replaced with a thin seed layer on an inexpensive substrate. The optical constants of the ITO layer were calculated from data taken on a Woollam variable angle spectroscopic ellipsometer. The experimentally determined optical constants of the ITO are implemented in the ellipsometry software, VASE, and used to calculate reflection, R(λ), from an ITO/Si stack of varying ITO thickness. Optical constants used for Si are from Green et al. [9].

3. Results and discussion

Figure 3 shows how the optimal ITO thickness varies with effective silicon thickness. For very thin cells, the short wavelength range of the spectrum is relatively more important than the long, weakly absorbed wavelengths. Hence, thinner ARCs will increase the efficiency of thin cells by shifting the reflectance minima towards shorter wavelengths. Therefore it is not surprising that the optimal ITO thickness increases relatively rapidly with increasing Si thickness for very thin cells. For effective silicon thickness greater than 10 μm, the optimal ITO thickness increases slowly until it finally stabilizes around 71 nm for effective silicon thickness greater than 30 μm. The ITOs are still sufficiently thick to avoid degradation of the electrical properties. For thicker effective layers the variation in transmittance becomes small and the variation of the IQE with wavelength dominates the weighting factor, hence it no longer varies with effective layer thickness. For a standard optimization, using only the AM1.5 spectrum [10] for weighting, the optimum ITO thickness is 79 nm. Figure 4 visualizes how the AM1.5 spectrum, IQE and Si thickness impact the weighting of the reflectance across the relevant wavelength range. Note that we use the effective Si thickness instead of the actual active layer thickness in order to account for arbitrary light trapping schemes.

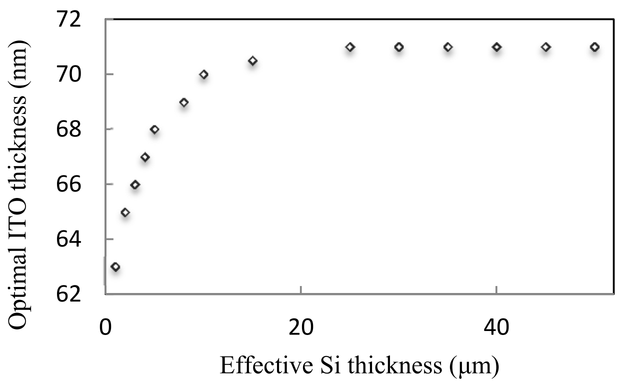

Fig. 3. The optimal ITO thickness depends on the effective thickness of the active silicon layer. The IQE is kept constant.

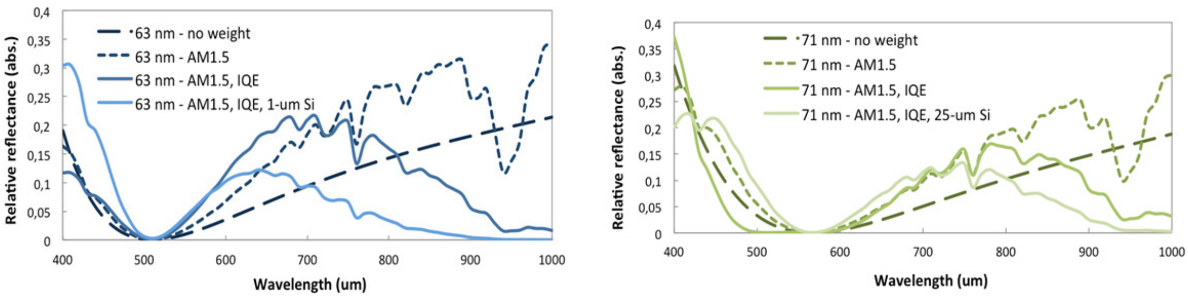

Fig. 4. The relative effect of weighting the reflectance of an ITO with thickness a) 63 nm, and b) 71nm with respect to the AM1.5 spectrum, IQE and Si absorption.

Parasitic absorption in the a-Si:H layer and free carrier absorption are accounted for in the weighting through their effect on the IQE. However, the wavelength range applied in the optimization, 400–1000 nm, excludes both the range most heavily affected by parasitic absorption (300-400 nm) and the range most heavily affected by free carrier absorption (1000-1100 nm).

Cell texture and oblique incidence will *increase* the optimum ITO thickness slightly. This is purely a geometric consideration of the path length difference between a ray reflected at the surface of the ARC and at the ARC/Si interface and comes in addition to the effect the texture has on the effective thickness of the cell. Taking the module glass into consideration, the angle of incidence of light hitting the *ARC* will always be less than 42°. The module glass is not included in the optimization of the ITO thickness.

4. Conclusions

In this work, a simple method to include electrical and physical properties of the cell into the optical modeling through an effective weighting function is established. While solar cell ARCs are often modeled using optical simulation tools and optimized for low integrated reflectance with respect to the AM1.5 spectrum, an enhanced solar cell efficiency can be achieved if also the transmittance and IQE of the cell is taken into account in the optical modeling.

For a 2-μm thick crystalline silicon heterojunction solar cell the optimal thickness of the Indium Tin Oxide (ITO) ARC is reduced by ~10 nm when IQE data and effective thickness are taken into account compared to only optimizing with respect to the AM1.5 spectra. The reduced ARC thickness will shift the reflectance minima towards shorter wavelengths and hence better match the absorption of very thin cells, where the short wavelength range of the spectrum is relatively more important than the long, weakly absorbed wavelengths. For this cell, we find that the optimal thickness of the ITO starts at 63 nm for very thin (1 μm) active Si layer and then increase with increasing T_e until it saturates at 71 nm for T_e > 30 μm.

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