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Multilayer antireflection coating design for $GaAs_{0.69}P_{0.31}$/Si dual-junction solar cells

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Abstract

In this paper, we systematically investigate the use of multilayer antireflection coatings (ARC) on $GaAs_{0.69}P_{0.31}$/Si dual-junction solar cells for achieving broadband reflection suppression. We incorporate dispersion, absorption, and both coherent and incoherent interference, by modeling the solar cell as a multilayer medium of thin films and a substrate, using the transfer matrix method. The analytical model is verified through reflectance measurements on a $GaAs_{(1-x)}P_x$/GaP stack. Our results show that optimized double- and triple-layer ARCs can minimize reflectance to below 5% within the spectral range of ~400–945 nm, with the latter maintaining this performance over a broader spectrum of 390–1000 nm, in comparison to 25–45% reflectance for the bare solar cell.

Keywords: Antireflection coating; Multi-junction solar cell; Transfer matrix method; $GaAs_{(1-x)}P_x$/silicon tandem cell

1. Introduction

Multi-junction solar cells (MJSCs) address the problem of energy loss due to thermalization and lack of absorption. By combining materials with different band gaps in a single cell, a higher fraction of the available solar energy can be converted into electrical energy. Despite their importance in achieving ultimate solar conversion efficiencies, MJSCs have been mainly used for space and highly concentrated terrestrial applications. The challenge of extending their use to one-sun or low-concentration terrestrial applications requires generating cost-effective, high-efficiency multi-junction solar cells (International Energy Agency, 2014).

In recent years, numerous studies have been conducted aiming at optimizing the solar cell structures of two or more junctions, using different band gap materials. Among the materials that have attracted tremendous interest are the III–V compounds, due to several advantages such as band gap tunability and high absorption, as well as fabrication advances that allow these layers to be grown on Si through the use of various graded buffers (Andre et al., 2005; Carlin et al., 2000; Geisz et al., 2006; Grassman et al., 2009, 2010; Lueck et al., 2006). This monolithic integration of III–V materials on Si platforms combines both the techniques and the tools from the Si manufacturing technology with the rich selection of different band gap materials of III–V compounds.

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As shown by Kurtz et al., a combination of band gaps of 1.1 eV for the bottom cell and 1.7–1.8 eV for the top cell leads to the highest theoretical efficiency (up to 37% under one-sun AM1.5G) for a dual-junction, series-connected cell (Kurtz et al., 1990), and this arrangement can be obtained by stacking a $GaAs_{(1-x)}P_x$ cell with a Si cell, connected by a tunnel junction.

In order to minimize energy losses due to reflection, antireflection coatings (ARCs) can be employed on top of the solar cells. Most of the studies on ARCs focus on single-junction solar cells (Aziz et al., 2011; Gangopadhyay et al., 2004; Zhao and Green, 1991). However, the design of effective antireflection coatings for multi-junction solar cells is indispensable to approach the high theoretical limits associated with those cells. Compared to the design of ARCs for single-junction cells, the main challenge with MJSC ARCs is related to the broader reflection suppression requirement, since the combination of the different subcells will absorb in a broader range of the solar spectrum. This additional requirement can be satisfied with multilayer ARC designs.

The literature on the study of antireflection coatings for III–V multi-junction solar cells can be grouped into two main categories – the number of junctions forming the solar cell, and the method adopted during the analysis. The Rouard method can be used to optimize the parameters associated with the design of multilayer antireflection coatings (Homier et al., 2012), while some of the reported studies use heuristic search methods, such as genetic algorithms (Schubert et al., 2008; Yan et al., 2013) to perform the same task. The transfer matrix method (TMM) (Conrad et al., 2014; Zhao and Green, 1991; Lu and Gang, 2007) is also effective for calculating the reflection spectra, and can easily take into account both the coherent and incoherent light behavior. All these research efforts, except for (Conrad et al., 2014), focus on triple-junction solar cells, where the top cell is based on GaInP.

The main focus of our work is to implement an analytical model to calculate and minimize reflection of a tandem solar cell through the use of multilayer antireflection coatings. We employ an approach based on the theory of quarter-wave dielectric layers and the transfer matrix method to determine the materials and the thicknesses of the layers forming the multilayer ARCs. The TMM approach offers the advantage of having complete control of the physical parameters of the ARC stack. As an advantage over the heuristic approaches, the analytical model allows one to assess the reflection suppression performance of the ARC under thickness deviations subject to the tolerance windows of the fabrication processes. Using this analytical model, we address the energy-related losses due to reflection (and hence reduced absorption of photons with energies above the band gap of the absorber layers), in a $GaAs_{0.69}P_{0.31}$/Si dual-junction solar cell. Our approach can be easily generalized to any solar cell structure with various numbers of junctions and materials, assuming that the optical constants of all the constituent layers are known. It can also be adapted to any number of ARC layers.

The number of junctions forming the solar cell determines the cell design and the respective materials to be used for maximizing the efficiency. These materials also determine the reflection response of the cell and the ARC design that is required to achieve optimum antireflection. The materials that are traditionally used in the literature to suppress reflection in solar cells set the basis for our material selection. That list of materials includes TiO_2, SiO_2, SiN_x, MgF_2, ZnS, ZnO, Al_2O_3, Ta_2O_5, SiC, AlON, and HfO_2.

With this material selection, we focused our work on the design of double-layer ARC (DLARC) and triple-layer ARC (TLARC) stacks. For the DLARCs, we used SiO_2/TiO_2 and SiO_2/SiC, and for the TLARCs we used MgF_2/HfO_2/SiC and MgF_2/HfO_2/TiO_2. TiO_2 has been used in this type of applications (Aiken, 2000; Jin et al., 2003; Lien et al., 2006). In addition, the use of SiC as antireflection coatings in Si-based solar cells (Klyui et al., 2002; Shen et al., 2012) and as dielectric gratings in thin-film solar cells (Esteban et al., 2010), due to its high refractive index and low extinction coefficient, has also been reported in the literature. Furthermore, SiC is known for its good passivation properties (Lee et al., 2012) and hence has been widely used as a window layer material in thin-film solar cells (Heidt et al., 2011; Kim et al., 2012; Yu et al., 2001). Thus, the proposed coating of MgF_2/HfO_2/SiC is expected to adequately meet both the passivation and antireflection requirements.

Our results show that the reflectance for the optimized triple-layer coating (using MgF_2/HfO_2/SiC) is less than 10% over the entire visible and near-infrared (NIR) spectrum, as opposed to 25% to 45% reflectance calculated for the bare $GaAs_{0.69}P_{0.31}$/Si solar cell. The optimized triple-layer design shows a significant improvement in the near-ultraviolet (NUV) band, over the optimized double-layer design. The solar spectrum weighted reflectance (SWR) over the entire spectrum of 300–1100 nm varies between 2.86% and 4.37% for the investigated triple- and double-layer designs, respectively, compared to 32.22% for the bare $GaAs_{0.69}P_{0.31}$/Si solar cell.

2. Materials and methods

In this paper, we implement the transfer matrix method to study the effect of antireflection coatings on the suppression of reflection at the top surface of a $GaAs_{0.69}P_{0.31}$/Si dual-junction, series-connected solar cell, which is treated as a multilayered medium in the model. TMM provides a systematic procedure for finding the transmittance and reflectance of a stack of dielectric layers of prescribed thicknesses and refractive indices. These input parameters are varied within a certain range, in order to find the combination that leads to the lowest reflection. The algorithm incorporates dispersion and absorption in each