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Analytical model for simulating thin-film/wafer-based tandem junction solar cells

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ABSTRACT

Replacing the present-day commercial single junction silicon (Si) solar cells with low cost, high efficiency solar cells is imperative, in order to compete with other existing energy technologies. Many research groups have looked into using III–V materials, tandem junction solar cells and thin-film technologies to reach higher efficiencies. However, many of these techniques involve expensive materials or costly manufacturing processes. In this research, we focus on a tandem junction solar cell design that is based on a thin-film perovskite top cell and wafer-based Si bottom cell. In order to analyze the performance of the tandem cell, an analytical model is needed to compute the quantum efficiency and characteristic solar cell data. The highly versatile Matlab-based analytical model presented in this work is capable of modeling different kinds of tandem cells based on a variety of solar absorber combinations. The model allows user to adjust input parameters, such as reflectivity, material thickness, donor and acceptor densities, and carrier lifetimes in order to optimize the quantum efficiency, maximum power output, open circuit voltage, and short circuit current quantities of the cell. Using this analytical model, we were able to design a perovskite and black Silicon (bSi) tandem cell, which reached an efficiency of greater than 30%.

1. Introduction

Wafer-based monocrystalline silicon (c-Si) solar cells reached a maximum efficiency of 25% (Green et al., 2016) in the 1999 and have improved little in recent years, prompting the research of different cell materials and designs to create cost competitive and higher efficiency cells. Several research groups are exploring different techniques to reach high efficiency in single junction solar cells, such as using III–V materials (Kayes et al., 2011) or by creating tandem junction cells with different absorbers (Yamaguchi, 2003). While III–V solar cells have reached efficiencies greater than 40% (Green et al., 2016), the materials and fabrication processes required to manufacture III–V at an industrial scale, are expensive.

Commercial scale Si solar cells exhibit average efficiencies of 17–19% because the 25% cell requires several costly processes to manufacture; for solar energy generation to be cost competitive, expensive manufacturing processes are not an option. Given the presence of extensive infrastructure to manufacture Si solar cells, it is only judicious that any low cost and high efficiency solar cell architecture utilizes Si. Nanostructured 'black silicon' (bSi) solar cells (Toor et al., 2016a, 2016b), which use an inexpensive chemical etching technique to form an antireflection (AR) coating on the Si surface have recently been developed and have reached a record efficiency of 22.1% in p-type c-Si in 2015 (Savin et al., 2015).

Even with better optical absorption due to bSi, the champion bSi solar cell efficiency remains at 22.1% relative to 25% for cells that do not utilize bSi AR. The reason for the lower efficiency of bSi solar cells is that they suffer from poor electrical performance when illuminated by blue light (350–475 nm light wavelength) due to a high surface area with dangling bond-like defects and high doping density that results in a high probability for electrons excited by light to relax back to their lowest-energy state, leaving no energy to collect. These effects result in low energy conversion efficiency for the blue wavelengths of bSi solar cells. Therefore, the use of lead-based hybrid perovskite layer to collect the blue light instead of bSi eliminates this as

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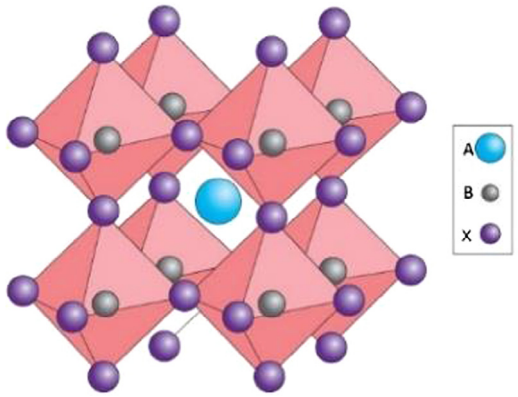

Fig. 1. The molecular structure of perovskite. Reprinted by permission from Nature Publishing Group: Nature Materials 13, 838–842 (2014), copyright (2014) License number: 3852560435429.

a problem for bSi. Thin-film perovskite solar cells, which are relatively cheap to manufacture, have demonstrated extremely rapid progress with the first 10.9% efficient cell demonstrated in mid-2012 and in early 2014 cells reached 17.9% (Green et al., 2014). Si has an intrinsic bandgap of 1.1 eV while the perovskite bandgap can be tuned over a wide range from 1.5 eV to 2.3 eV. Based on these bandgaps, Si and the perovskite make an excellent pair for tandem solar cell architecture that can revolutionize solar energy generation due to the high efficiency and low cost potential.

Perovskites are materials described by the formula ABX_3, where X is an anion, A and B are cations of different sizes (A being larger than B) (Chilvery et al., 2015). In this work, A will be an organic cation, specifically, methylammonium (MA) ($CH_3NH_3^+$); B will be an inorganic cation, lead (Pb), and X will be a halide anion based on iodide (I^-), or a mixed iodide and bromide, I_{3-x} Br_x, or iodide and chloride (I_{3-x} Cl_x). A schematic molecular structure of the perovskite is shown in Fig. 1.

Perovskite semiconductors have attracted attention since the beginning of their incorporation into photovoltaic devices by Miyasaka et al. in 2009, with cells exhibiting 4% efficiency (Kojima et al., 2009). Since 2009, there has been extremely rapid progress with the first 10.9% efficient cell demonstrated in mid-2012 to 17.9% cells in early 2014. The perovskite absorber properties that are desired for this work include a larger bandgap than Si that enables the necessary optical properties and longer diffusion lengths. Due to the tunable bandgap of perovskites (1.5–2.2 eV), they are ideal candidates to be paired with Si, in order to obtain a highly efficient cell. However, perovskite solar cells have been known to degrade due to exposure to UV light and humidity. Recent research has addressed this issue of degradation by adding a protective coating to the perovskite based solar cells. For example, Koushik et al. (2017) proposed atomic layer deposition (ALD) based aluminum oxide (Al_2O_3) coating and Rajamanickam et al. (2016) demonstrated solution processed graphene-polyaniline (PANI) composite as effective coatings to reduce the degradation of perovskite solar cells. Hence, our research focused around a tandem junction solar cell design comprised of the thin-film, lead-based perovskite top cell and wafer-based Si bottom cell. This research demanded a new analytical model since PC1D (Lien and Wuu, 2009) and SCAPS (Minemoto and Murata, 2014), the two leading solar cell modeling programs, were incapable of modeling our specific solar cell as the programs result in convergence errors.

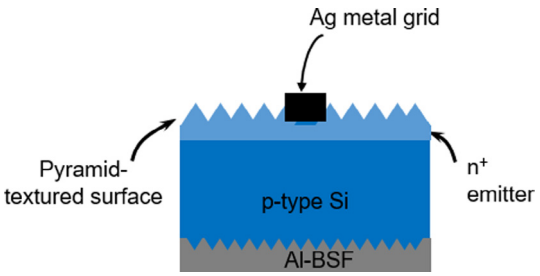

Fig. 2. Structure of a single junction Si solar cell with surface texturing, aluminum back surface field, and silver contact.

2. Methodology

2.1. Matlab-based analytical model

The Matlab model was designed in conjunction with the structure of a typical solar cell as shown in Fig. 2. Photocurrents are generated in three regions of the p-n junction device: the base, emitter, and the space charge region or the depletion region. The base is a p-type Si substrate and is the thickest absorber of the cell. The emitter is highly doped n-type Si with surface texturing in order to reduce surface reflection and increase light absorption. The depletion region is where the p-type substrate and n-type substrate meet, and while the photocurrent is small in this region, the calculation cannot be ignored (Sze and Ng, 2006). The back surface field (BSF) is the bottom layer of the cell and consists of a highly doped material (Fig. 2 shows an aluminum BSF). The BSF reduces rear surface recombination, which adversely affects the short circuit current and open circuit voltage. In our model, the BSF of the cell is simulated by decreasing the rear surface recombination velocity for electrons according to Sze and Ng (2006) (see Table 1).

Table 1
Constants used in Matlab analytical model.

Symbol	Parameter	Value
q	Charge of electron	1.602×10^{-19} C
h	Planck constant	6.626×10^{-34} J-s
k	Boltzmann constant	1.3807×10^{-23} J/K
c	Speed of light	299,792,458 m/s
n	Refractive index of air	1

Table 2
Input parameters of the model.

Symbol	Parameter	Units
N_d	Donor density	cm^{-3}
D_p	Hole diffusion coefficient in emitter	cm^2/s
τ_p	Hole lifetime in emitter	s
L_p	Hole diffusion length in emitter	cm
N_a	Acceptor density	cm^{-3}
D_n	Electron diffusion coefficient in base	cm^2/s
τ_n	Electron lifetime in base	s
L_n	Electron diffusion length in base	cm
W	Depletion width	cm
H	Thickness of substrate	cm
x_j	Junction depth of n+ region	cm
S_n	Surface recombination velocity for electrons	cm/s
S_p	Surface recombination velocity for holes	cm/s
E_g	Band gap energy	eV
N_c	Conduction band effective density of states	cm^{-3}
N_v	Valence band effective density of states	cm^{-3}
T	Temperature	K
H	Total cell thickness	cm
λ	Wavelength	nm