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A new proposal for Si tandem solar cell: Significant efficiency enhancement in 3C–SiC/Si

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ABSTRACT

In order to considerable enhancement of the efficiency of silicon solar cells, in this paper, for the first time, we present a new proposal for silicon based tandem solar cells. For investigation of this idea, we have evaluated the characteristics of 3C–SiC/Si crystalline tandem solar cells connected series by a tunneling junction, under air mass 1.5 global irradiance spectrums. A 2D simulation including the effects of surface passivation, back surface field (BSF), and carrier tunneling have been performed to obtain the optical and electrical characteristics of single junction silicon, 3C–SiC, and finally the tandem cells. The obtained data illustrate that the best design parameters considering the experimental limitations can be obtained. High energy conversion efficiency for the proposed structure of 26.09% has been achieved for 3C–SiC/Si tandem structure driven by 20.49% and 17.86% conversion efficiencies of single junction Si and 3C–SiC solar cells, respectively. Our results justifies that the higher conversion efficiency of the Si-based tandem structure compared with 3C–SiC and Si cells stems from enhancement of open circuit voltage and fill factor parameter at the hands of decrease in short circuit current limited by the top 3C–SiC cell.

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1. Introduction

Tandem solar cells provide an effective way to harvest a broad spectrum of solar radiation by combining two or more junctions with different absorption bands. However, tandems based entirely on crystalline silicon and its compounds would have many attractions, as they would retain the strengths of silicon technology, (durability, non-toxicity, and material abundance), while giving the design flexibility offered by other less-attractive material systems [1]. In the last decade silicon carbide (SiC) has been given renewed attention as a potential material for high voltage and high power applications [2,3]. SiC is a preeminent material for 21th century and is anticipated that the photovoltaic industry may take advantage of this situation [4]. Silicon carbide exists in 250 crystalline forms [5] (called polytypes) which each structure has its own unique electrical and optical properties. Cubic silicon carbide (3C–SiC) as one kind of the mentioned structures, exhibits excellent electronic properties including high electron mobility and saturated electron drift velocity [2]. 3C–SiC with an indirect band gap of $E_g = 2.2$ eV, compared to the other polytypes ($E_g = 2.8$–3.2 eV) is more suitable for top cell of silicon-based tandem cells where SiO_2 or 6H–SiC could be used as surface passivation agent [6,7]. Recently, several reports have been focused on silicon tandem cells such as silicon quantum-dot superstructure-based tandem solar cells [8] and InGaN/Si tandem solar cells with efficiencies of 26–29% (based on the material quality) [9]. However, there have not paid enough attention to 3C–SiC as a top cell for crystalline silicon tandem solar cell till now. This paper presents a 2D simulation of tandem 3C–SiC/Si solar cell, using finite element method (FEM). Our simulation consists of silicon and 3C–SiC single junction and a silicon tunneling diode (p^+/n^+ silicon) separately, in addition to connection of the individual cells through a low resistance tunnel junction. It has been covered that surface passivation and back surface field play a key role in improving crystalline solar cell performance as they reduce surface recombination [10]. Here, we will discuss the effect of these parameters on efficiency optimization of the designed tandem solar cell. First, we have simulated a single junction silicon solar cell with optimized parameters that the obtained results are in good agreement with practically and theoretically reported results for single junction solar cells. Similar simulations have been performed for PN junction 3C–SiC single junction solar cell. Operation characteristics of the tunnel junction as connection region between the individual cells have been evaluated and finally, the structural performance of the whole tandem cell was obtained.

2. Structure modeling

We have considered all the actual parameters (like absorption coefficient, carrier mobility, recombination coefficient, doping

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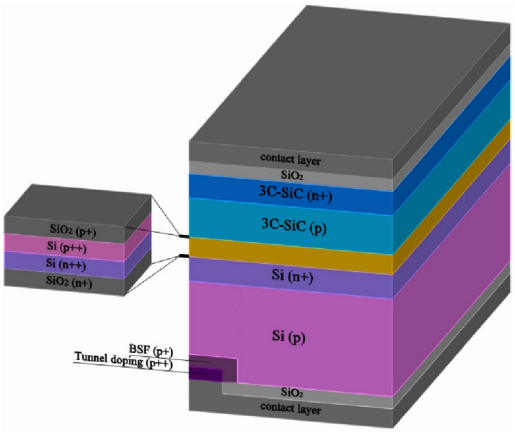

Fig. 1. 3C–SiC/Si tandem solar cell cross section.

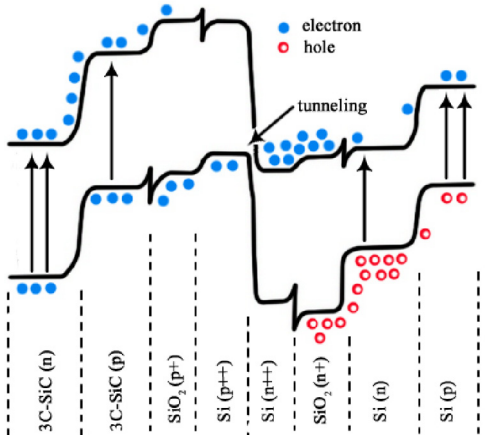

Fig. 2. Carrier transport in 3C–SiC/Si tandem cells.

profiles like Gaussian doping profile for n type region, metal contacts) in our simulation, as our goal is to investigate the theoretical achievable efficiencies that are in agree with practical. Fig. 1 schematically shows the considered tandem solar cell layers.

Tandem solar cells provide an effective way to harvest a broad spectrum of solar radiation by combining two or more materials with different absorption bands (different band gaps) and the light shines from the larger band gap side of the solar cell (the top cell). Carrier tunneling through the common junction is critical part of carrier transport in highly doped PN-junction solar cells. Fig. 2 illustrates the carrier transport mechanism in the proposed tandem cells. The incident light creates an electron-hole pair in the bottom cell, the electron may tunnel from conduction band to the valance band of the top cell and then, transport to the conduction band of the top-cell material by a high energy photon. This tunneling mechanism from the potential barrier describes the current mismatching solution.

To model the considered tandem cell, conventional drift-diffusion model have been solved which basically contain three equations governing the electrostatic potential, electron and hole continuity [11,12]. For generation term, we have used global AM1.5 spectrum [13] and generation rate is calculated at each mesh point from the incident solar flux and absorption coefficient. Also, the recombination rate is based on the Shockley-Hall-Read and Auger recombination [14–16]. If a sufficiently high electric field exists within tunnel junction, local band bending may be sufficient to allow electron to tunnel from the valance band into the conduction band. This generation mechanism is implemented

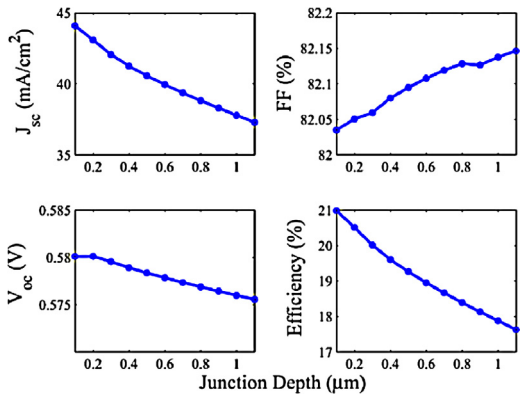

Fig. 3. The variations of the V_{OC}, J_{SC}, FF and efficiency as a function of junction depth.

into the continuity equations through the tunneling generation rate defined by $G_{BBT} = B_0\ E^{\sigma}\ \exp\ (-E_0/E)$ with E being the electric field and B_0, σ and E_0 being constants. For these parameters we use Klaassen model [17–19]. The values for these constants are $B_0 = 4 \times 10^{14}\ \mathrm{cm^{-1/2}\ V^{-5/2}\ s^{-1}}$, $B_0 = 1.9 \times 10^7\ \mathrm{V/cm}$ and $\sigma = 2.5$ for indirect transitions. Conversion efficiency is the most important property of a solar cell which is defined as the ratio of the photovoltaically generated electric output of the cell to the radiative power falling on it [20]. Mathematically, it is defined by $\eta = P_{out}/P_{in} = (FF \times I_{sc} \times V_{oc})/P_{in}$, where FF denotes the fill factor and is defined as ratio of $V_m I_m / V_{oc} I_{sc}$, with I_{sc}, V_{oc}, V_m, and I_m being the short circuit current, open circuit voltage, voltage and current in maximum power, respectively P_{in} is power of incident light which is $P_{in} = 0.1\ \mathrm{W/cm^2}$ atone sun condition. Quantum efficiency and spectral response are other two important parameters that are calculated to show their effect in the device operation. The former parameter is defined as the ratio of the carrier numbers collected by the solar cell to number of photons in a given energy incident on the solar cell. Also, spectral response is the ratio of the current generated by the solar cell to the power incident on the cell.

3. Simulations and results

3.1. Single junction silicon and 3C–SiC solar cells

In this section a single PN-junction (the bottom cell for our tandem structure) silicon solar cell has been simulated and optimized to achieve practically reported efficiencies. It has been shown that such a structure can satisfy efficiencies exceeding 20% both theoretically and experimentally [21,22]. We consider appropriate BSF and dielectric rear passivation to reduce the surface recombination rate. A thin heavily-doped layer was placed near the contact to create an ohmic back contact via tunneling. We nominate this doping level as tunnel doping. Junction depth is another parameter which we have optimized the designed cell according to this parameter that defines the depth of the plane in PN-junction at which concentration of acceptors equal to the concentration of donors. A silicon solar cell with 200 μm height and 500 μm width has been considered to obtain open circuit voltage (V_{oc}), short circuit current density (J_{sc}), fill factor (FF) and efficiency (η) that SiO_2 or Si_3N_4 used for rear passivation. Doping profile is assumed Gaussian in n-type side and uniform in other side of the junction. The values for dopant concentrations are $N_{dpeak} = 1 \times 10^{20}\ \mathrm{cm^{-3}}$ for n-side, $N_a = 1 \times 10^{17}\ \mathrm{cm^{-3}}$ for p-side and $N_{BSF} = 1 \times 10^{19}\ \mathrm{cm^{-3}}$. First, we highlight the tunnel doping concentration and junction depth optimization. Evaluated results of the introduced cell as functions of junction depth and tunnel junction doping concentration are shown in Figs. 3 and 4, respectively.

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