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Numerical simulation of rear contact silicon solar cell with a novel front surface design for the suppression of interface recombination and improved absorption

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ABSTRACT

Nanostructuring has been projected as an appropriate technique to make thin silicon an efficient absorber. Although nano-textured surfaces have shown an anti-reflective effect, their surface passivation properties are found to be generally worse compared to standard micro-textured surfaces. Here, a novel front surface design has been proposed and simulated to balance the photonic and electronic effects together. ZrO_2 based texturing has been used along with SiC-based front surface passivation for the suppression of interface recombination and improvement of open-circuit voltage (V_{OC}). The device under investigation shows record V_{OC} of 662 mV in the sub-10 μm-thick rear contact silicon solar cell. The presence of ZrO_2 and SiC significantly improves the optical as well as the electrical behavior of the device. The device exhibits external quantum efficiency (EQE) > 81% in the spectrum range of 320–720 nm wavelength spectrum with a maximum of 95.6% at wavelength 560 nm. These improvements lead to 15.7% efficient rear contact silicon solar cell, in the sub-10 μm-thick regime. In second approach power conversion efficiency (PCE) of 21.6% has been achieved, by introducing the same front surface design to a 300 μm thick device. All the simulations have been done using calibrated software program in ATLAS device simulation.

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1. Introduction

Photovoltaic (PV) is a simple and elegant method of coupling the sun's energy. Solar cells are exceptional in that they directly convert the incident solar radiation into electricity, with no pollution and noise, making them robust, reliable and long lasting. Solar cells are attractive candidates for clean and renewable power [1]. Silicon (Si) is the most extensively used material for solar cell production due to its abundance, reliability, nontoxicity, and mature fabrication techniques. Further, solar cell technology is a function of efficiency, cost, and a lifetime of the cell. Hence, large-scale implementation is not economically feasible. To absorb the solar spectrum, the thickness of the planar cell is typically more than 100 μm [2]. This requirement results in higher cost. Also, in order to increase the collection of the generated carriers, the dimension of the device should be comparable to the carrier diffusion length. Thinner silicon solar cells with high efficiency are fruitful for cost-effective energy solution [3,4]. Further, to maximize solar cell efficiency, it is necessary to optimize both, the device electrical characteristics and the optical absorption of thin devices [5,6]. Nanostructuring has been projected as an appropriate method to make thin silicon an efficient absorber. However, these cells are not efficient due to Auger and surface recombination as the surface to volume ratio of the cells is large. However, recently, methods to minimize the surface recombination for nanostructured based ~300 μm thick devices have been presented which results in 20% and 22% efficient cells [7,8]. The PCE of nanostructured Si solar cell remains below 22.2% for thick devices [7,8] and below 11% for thin devices [9], except 13.7% and 15.7% reported in Refs. [9,10] for the 10 μm thick devices. In previous work, a 14.3% efficient ZrO_2 textured rear contact solar cell has been proposed. The work shows efficient photon absorption in the sub-10-μm-thick device [11]. ZrO_2 is a material of great technology due to its outstanding mechanical and electrical properties and high dielectric constant. Large band gap (E_g ~ 6eV) and dielectric properties (ε ~ 25) suggested its potential to replace SiO_2 in the advance semiconductor device and optical applications [12]. Also, it has an excellent thermal stability. This work further extends the study of ZrO_2 textured front surface based

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rear contact silicon solar cell having thin defect free SiC layer at the ZrO_2/Si interface. The presence of thin SiC layer minimizes the reflectivity [13,14]. Previous work shows, embedding 3C-SiC nanoparticles significantly reduces the photo reflectivity in UV/visible spectrum region [15]. The SiC is an indirect (Eg = 2.2 eV) semiconductor with wide energy band gap, high thermal conductivity, large breakdown field, and high saturation velocity make this material an ideal choice for high temperature, high power, high voltage electron devices. Its high melting point, chemical inertness, high wear resistance, and extreme hardness, make it possible to fabricate sensors and actuators capable of performing in harsh environments [16]. The SiC film formation has been done for Si solar cell passivation. The film was deposited on silicon (100) and glass substrates by an RF magnetron co-sputtering system [17]. Recently, SiC passivated SiGe wafer based rear contact solar cells have been proposed for ultra-high efficiency in sub 10 μm thick devices; work shows improved optical absorption without the need of complex texturing [18,19].

Moreover, this work shows that the presence of SiC improves the photovoltaic parameters of ZrO_2 based rear contact solar cell. The discussed device shows J_{SC} and V_{OC} of 29.3 mA cm^{-2}, 662 mV respectively. This results, in 15.7% PCE in sub 10-μm thick solar cell, which is equivalent to the experimentally achieved record PCE of 15.7% using periodic nanostructure [10]. However, present work shows superior V_{OC}, which shows that the surface recombination issue has truly been solved and SiC passivation based nanostructured silicon solar cell have real potential for industrial production. The rear contact silicon solar cell has been selected because it is a promising high-efficiency solar cell having both, junction and the electrodes at the back side of the device. Now, since the junction and contacts are on the back side, front surface can be designed for optimum optical performance [20].

2. Device structure and simulation

In this section, the calibrated software program is written in Silvaco ATLAS device simulator as per the results reported by (*sangmoo jeong* et al., *2013*) for 10 μm thick rear contact solar cell with antireflection (AR) coating [9]. The dimensions and the doping density of the planar device were identical to the referenced cell and named as Device A as shown in Fig. 1. The device geometry in the simulation was (50-μm-wide pitch, 46 μm-wide *P*+, and 30-μm-wide *N*+). The substrate was *N-type*, with doping density (3×10^{15} cm^{-3}). *P*+ region was doped with boron (4×10^{20} cm^{-3}, depth of 300 nm). *N*+ region was doped with phosphorous (1×10^{20} cm^{-3}, depth of 100 nm).

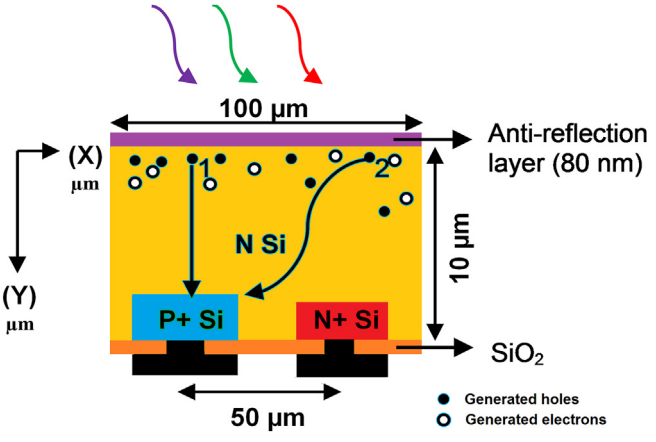

Fig. 1. The simulated device structure i.e. 10 μm thick rear-contact silicon solar cell with the anti-reflective (AR) coating.

Further, in the presence of heavy doping, (>10^{18} cm^{-3}), experimental work has shown that the *PN* product in silicon turns out to be doping dependent [21]. As the doping level rises, a decrease in the bandgap occurs, where the valence band raises by the approximately same amount as the conduction band is lowered. Discussed structure has heavily doped *P* and *N* regions, and so bandgap narrowing effects are enabled. These effects can be described by an analytic expression relating the variation in the bandgap, ΔEg to the doping concentration, N [22]. Furthermore, the solar cells are the carrier recombination affected devices. Therefore, Auger and Shockley- Read- Hall (SRH) recombination models are selected during the simulation. Phonon transitions occur in the presence of a trap or defect within the forbidden gap of the semiconductor [23,24]. Basic for the SRH model are the assumptions of one trap level in the forbidden band and drift-diffusion assumption for the transport of electrons and holes, and the assumption that the dynamics of the trapped carrier is quasi-stationary [25]. Auger recombination occurs through a three particle transition whereby a mobile carrier is either captured or emitted. The underlying physics of such processes is unclear, and normally a more qualitative understanding is sufficient [26]. The auger coefficients, $C_p = 9.9 \times 10^{-32}$ cm^6 s^{-1} and $C_n = 2.8 \times 10^{-31}$ cm^6 s^{-1} have been used for *P*-type and *N*-type silicon, respectively, at 300 K temperature [27]. The concentration dependent mobility and field dependent mobility models have also been selected during simulation. The consistent set of models and parameters for the simulation of Si solar cell have been used as suggested in already published article [28].

To obtain the current density (J)- voltage (V) curve under illumination, the standard AM1.5 solar spectrum has been used. Also, as the contact interface between metal and semiconductor is highly doped both for the *P*+ and *N*+ region i.e. ~10^{20} cm^{-3}, therefore, the ohmic contacts are used in this work. This has been done to avoid Schottky barriers, and thus unnecessarily higher computation time. Result reveals, the software program, is well calibrated within the acceptable range shown in Table 1.

3. Results

The result section is divided into two parts, first, designing a ZrO_2 textured and thin SiC-based ZrO_2 textured 10 × 10 μm thick *N-type* silicon wafer for optimal spectrum response and second, the designed ZrO_2 pattern with and without SiC has been introduced to Device A, by removing anti-reflective coating (ARC) layer. ZrO_2 textured 10 μm thick rear contact silicon solar cell is called as Device B, and ZrO_2 textured device with SiC layer at the ZrO_2/*N*-Si interface is termed as Device C.

3.1. Spectrum response of ZrO_2 textured SiC-based silicon wafer

In this section, a 10 × 10 μm thick *N*-type Si wafer without ARC, with ARC, textured ZrO_2 and textured ZrO_2 having SiC (20 nm) layer at ZrO_2/*N*-Si interface have been designed and simulated to obtain the spectrum response. The entire front surface is covered with repeated ZrO_2 facet structures and optimized height, 175 nm, and width, 250 nm is used for texturing. The smaller and larger width size than 250 nm will show lower optical coupling and lower conversion efficiency, as suggested in Ref. [29]. In the real cell, the nanopatterns can be fabricated via inexpensive and scalable imprinting technique. The complex refractive index of various materials has been obtained from Sopra database [30] and presented in Fig. 2 (a–b). Fig. 2a shows, as wavelength changes from 300 to 1200 nm, the reflective index, n of ZrO_2 changes from 2.45 to 2.17. the n values of ZrO_2 are close to the n values of nitride, which is

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