Simulation of high efficiency silicon solar cells with a hetero-junction microcrystalline intrinsic thin layer

Mehdi Hamid Vishkasougheh *, Bahadir Tunaboylu

Industrial Engineering, Istanbul Şehir University, Altunizade Mah. Kuşbakışı sok, No: 27, Üsküdar, Istanbul, Turkey

ARTICLE INFO

ABSTRACT

The solar cells using silicon technology have been modeled and fabricated reaching 19% cell efficiency in the past. In an effort to maximize efficiency and reduce cost to reach the grid parity, thin films of silicon are being investigated. In this study, a solar cell hetero-junction with an intrinsic thin layer (HIT) was simulated on a p-type substrate, which can be manufactured with standard silicon manufacturing processes. The influence of different parameters such as the temperature, the back surface field, different layer thicknesses, different doping concentrations for p and n type layers, ZnO and ITO as transparent conductive oxides with plane and texturized surface shapes and densities of interface defects (D_{it}) on the efficiency was investigated. For simulation of hetero-structures, AFORS-HET software was used in the study. Our results indicate that by optimizing different parameters of hetero-structure thin films, a high performance can be obtained using nanostructured surfaces up to an efficiency of 25% for HIT silicon solar cells. Optimized design parameters for HIT silicon solar cell for fabrication are proposed.

© 2013 Elsevier Ltd. All rights reserved.

1. Introduction

Hetero-junction with intrinsic thin-layer (HIT) solar cells, developed by Sanyo Ltd. in 1994, offer low cost fabrication for a high-efficiency solar cells compared to crystalline silicon solar cells with diffused p–n junctions [1–4]. Fabrication of HIT solar cells is comparatively simple and more importantly, does not require high temperature steps. Thinner and lower grade silicon wafers typically experience wafer bowing in the high temperature, the back-surface field (BSF) process [1,3] can be used in this low-temperature (<200 °C) process [5]. This feature could also result in additional cost savings. HIT solar cells consist of ultra-thin amorphous silicon on crystalline silicon absorber layers. The a-Si:H/c-Si hetero-interface is of functional importance because the junction properties determine solar cell efficiency. In this investigation, a thin micro-crystalline intrinsic silicon layer is considered between the a-Si:H/c-Si hetero-interface to suppress the carrier recombination at this junction. Also the hydrogen dilution is reported to be a key deposition parameter that controls the film quality and phase formation [6,7]. Though SANYO's original design used a n-type substrate as the absorber for the HIT solar cell, the current research concentrates on developing the HIT solar cell on a p-type substrate because of its popularity in the photovoltaic industry [8].

Al-BSF is usually applied because of its easy fabrication process [9,3]. However, processing at a high-temperature (850 °C) could lead to the degradation of lower grade Si wafers. An alternative is to use a-Si:H(p+) to create the BSF for p-type c-Si that could be deposited at low processing temperatures (<200 °C). Efficient crystalline silicon heterojunction solar cells were fabricated on p-type wafers using amorphous silicon back contact layers [10]. In comparison, Al-BSF, an alternative material with larger conduction band offsets, could provide a much more effective mirror for the minority carrier electrons and a low back surface recombination. This leads to higher solar cell performance. However, the disadvantage of this material is that the larger band offset in the valence band edges would present a large barrier for majority carrier holes to flow through to the back contact [11].

It is well-known that the performance of a hetero-junction cell critically depends on densities of interface defects (D_{it}). Experimentally, the D_{it} can be modified by a hydrogenated termination of the Si wafer surface [12] or by passivating the defects by deposition of a thin μc-Si:H(i) layer [2].

Even if optimum parameters are utilized, solar cell efficiency is greatly limited by recombination at the transparent conductive oxide TCO/a-Si:H(n) interface. With the high work function of transparent conductive oxide (ΦTCO), an electron injection barrier develops at its interface with a-Si:H(n). This barrier limits the open-circuit voltage Voc by upwards band bending that develops at the TCO/a-Si:H(n) interface [13]. Hence, the value of ΦTCO should be carefully tuned to obtain the highest quality solar cells.

We used numerical computer simulation to address this issue. We investigated the influence of (a) μc-Si:H(i) layer as buffer, (b)

* Corresponding author. Tel.: +90 5319246864.
  E-mail address: mehdihamid@std.sehir.edu.tr (M.H. Vishkasougheh).

back surface field, such as a-Si:H(p+), (c) D_{it}, (d) two different transparent conductive oxide layers such as ZnO and ITO with texturized and planar surfaces and (e) temperature on solar cell performance. Finally, the optimal parameters were determined. The AFORS-HET (automat for simulation of hetero-structures) software was used as the numerical simulation tool. Its reliability was proven by many references [8,14].

2. Modeling

AFORS-HET has been proven as a convenient and effective means to study the role of various parameters on the performance of HIT solar cells [5,15]. The simulated basic structure of the solar cell was TCO/a-Si:H(n)/μc-Si:H(i)/c-Si(p)/a-Si:H(p+) as shown in Fig. 1. Oxygen defects in c-Si were chosen to be located at 0.56 eV above the edge of the valence band. For the density of localized states in the band gap of amorphous silicon it has been assumed that there are both acceptor-like states and donor-like states mod-
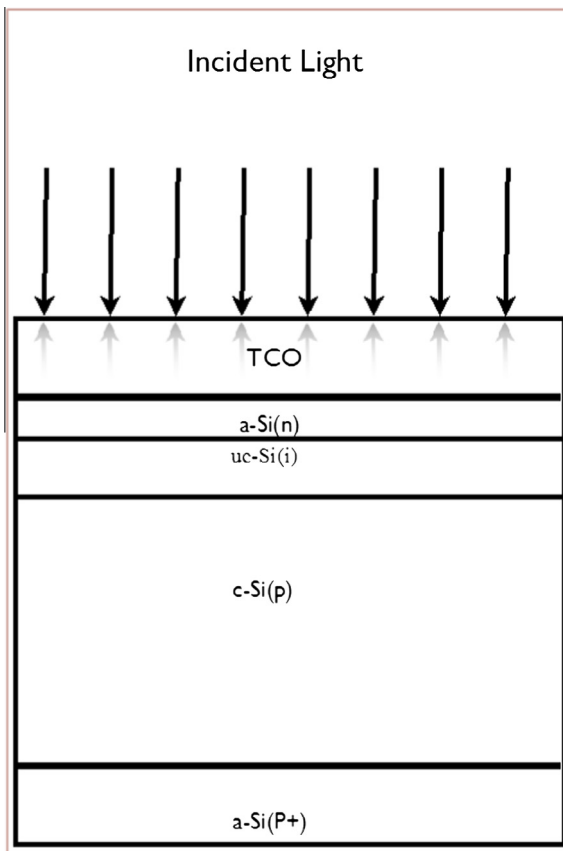
eled by exponential band tails (Urbach tails) and Gaussian mid-gap states (associated to silicon dangling bonds) [16]. The defect-state distributions for different layers such as the a-Si:H, μc-Si:H , and the a-Si(p+) base were set with the distributions depicted in Fig. 2 [17]. Some of the simulation parameters, such as a-Si:H layers, and the c-Si(p) base are the default values in the AFORS-HET software that can be found in Table 1. Fig. 3 shows texturized front surface of TCO in a schematic view.

In terms of illuminated current voltage characteristics, the global solar spectrum of 1 Sun of AM1.5 was studied with a power density of 100 mW/cm². The device temperature was considered as 300 K. The flat band was applied to the front and back contacts to prevent a contact potential. The light reflection on the front and back contact was set to be 0.1 and 1, respectively.

3. Results and discussion

3.1. Optimization of emitter layer

It was observed that as the thickness is reduced, the current becomes higher. There is difficulty in practice manufacturing a repeatable thickness value less than 3 nm, therefore the most realistic thickness is 3 nm. Using this thickness, an excellent efficiency can be obtained by the solar cell. According to Ref. [18], the thickness d of a-Si:H layer shows an optimal value in the range 5 nm < $d \leqslant$ 10 nm for an application as an emitter. This proves that the simulation results correlate with experimental findings.

As it can be seen from Fig. 4a, it is possible to optimize a solar cell structure for achieving the highest efficiency. We have obtained efficiency levels greater than 20%.

3.2. Optimization of the intrinsic layer

While SANYO developed HIT solar cells with a very thin intrinsic a-Si:H(i) layer inserted between different type a-Si:H and c-Si, it should be noted that there is a controversy about the need of such a layer [10]. Some authors claim that it is beneficial, while others get good results without it and do not see significant improvements if they introduce it. In this investigation μc-Si:H(i) was used, one reasonable explanation for the benefit of this undoped buffer layer is that the density of states in undoped μc-Si:H is weaker than in doped a-Si:H. Therefore, we can expect to have less interface defects when the heterointerface is formed with undoped μc-Si:H rather than doped a-Si:H.

AFORS-HET was used for finding the optimum thickness of this μc-Si:H intrinsic layer. Fig. 4b exhibits the effect of thickness of this layer on the solar cell external current, for a range of 3–10 nm. Solar cell external current reduces and by considering this fact that the current amount has direct impact on the final efficiency, therefore the efficiency will decrease. Our simulation results show good correlation to the experimental results from Ref. [19].

V_{oc} depends little upon the defect density or the thickness of the intrinsic layer. Furthermore, the value of V_{oc} is mostly controlled by the fairly simple physics of the splitting of quasi-Fermi-levels in

Fig. 1. A schematic for the basic structure of simulated solar cell TCO/a-Si:H(n)/μc-Si:H(i)/c-Si(p)/a-Si:H(p+) is shown.
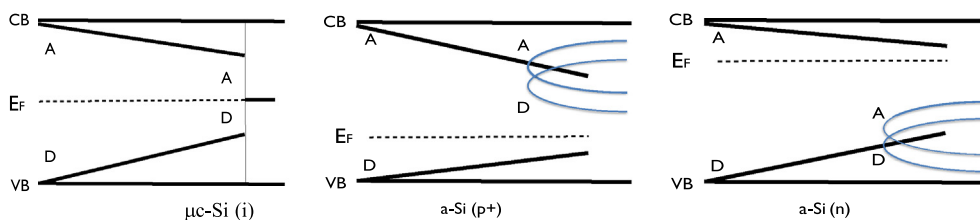

Fig. 2. Representations of defect state distributions of μc-Si(i) (left), a-Si(p+) (middle) and a-Si(n) (right) layers in the simulations are provided.