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# Two-dimensional simulation studies on high-efficiency point contact back heterojunction (a-Si:H/c-Si) solar cells

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## Abstract

The paper reports on the simulation studies of silicon based point contact back heterojunction solar cells using Silvaco Atlas tools. We also make use of band alignment diagrams connecting the entire cross-section of the device, from the emitter to the back surface field, to appreciate the operation of the solar cell. The effect of bias conditions on the band diagram and solar cell performance is explored. The influence of doping in the a-Si:H layer on the performance parameters is also investigated. In performing our investigation, we consider an optimized solar cell that shows a high efficiency of 24.49%, with a $V_{oc}$ of 0.76 V, $J_{sc}$ of 38.29 mA/cm$^2$, and FF of 84.2. Further improvements in efficiency can be potentially achievable by using texturization and front surface field.

*Keywords:* Interdigitated point contact solar cell; Back heterojunction solar cell; Silicon based back heterojunction solar cell; Photovoltaics; Device modeling; Energy band diagram

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## 1. Introduction

Back heterojunction (BHJ) solar cells have recently attracted significant research attention because of their perceived potential high performance. A BHJ solar cell (Diouf et al., 2010a,b; Herasimenka et al., 2009; Lu et al., 2007, 2009, 2011; Stangl et al., 2009; Tucci et al., 2008; Mingirulli et al., 2011; Choi et al., 2012; Haschke et al., 2012) combines the advantages and fabrication methods of front heterojunction cell (SANYO type a-Si:H/c-Si cell) (Kinoshita et al., 2011) and back junction c-Si cell (SunPower type cell) (Smith et al., 2012). A SANYO type solar cell is a high open-circuit voltage ($V_{oc}$) technology solar cell with $V_{oc}$ of 0.745 V, short-circuit current density ($J_{sc}$) of 39.38 mA/cm$^2$, fill-facto (FF) of 80.9%, and efficiency of 23.7% (Kinoshita et al., 2011). In this case, maximum processing temperature is ~260 °C, and an intrinsic a-Si:H layer is used for surface passivation. On the other hand, a SunPower solar cell is a high current density technology solar cells, with a $V_{oc}$ of 727 mV, $J_{sc}$ of 40.0 mA/cm$^2$, FF of 81.2%, and efficiency of 23.6%, with a peak efficiency of 24.1% (Smith et al., 2012). The important features of this technology are grid-less front side and interdigitated point contact structure at the rear side. Thus, by combining these two technologies, such as in a BHJ solar cell, high $V_{oc}$ and $J_{sc}$ can potentially be obtained.

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Recent experimental works on BHJ solar cells have shown efficiency up to 20.3% (aperture area efficiency) (Mingirulli et al., 2011) and 22.3% (Choi et al., 2012). Our recent work on modeling of BHJ solar cells based on a heterostructure between amorphous silicon (a-Si:H) and crystalline silicon (c-Si) (Jeyakumar et al., 2013) has also shown the potential of such solar cells, where it was found that an efficiency of at least approximately 19% is possible with an optimized emitter band gap of about 1.72 eV.

In light of the above discussion, and the potential that these solar cells have displayed, it becomes important to understand the effect of different parameters on the performance of the BHJ solar cells, as well as explore the limits on the potential. In this modeling work, we investigate the influence of different parameters in the performance of a BHJ solar cell. The solar cell under study has been further optimized, and demonstrates a theoretical potential efficiency of 24.49%. In performing our study, we also make use of a single continuous band alignment diagram connecting emitter and back surface field as an aid to qualitatively understand the charge carrier collection by their respective electrodes.

## 2. Device simulation models and parameters

Figs. 1 and 2 depicts the schematic cross section and rear side geometry of the BHJ cell. The various dimensions mentioned in the figure are utilized in our reported results here. We consider a 200 μm thick c-Si as the starting substrate with n-type doping concentration of $1.0 \times 10^{15}\ \text{cm}^{-3}$ and a minority carrier life-time ($\tau$) of 5 ms (Diouf et al., 2010a; Lu et al., 2011). Since there is no gettering in a-Si:H based processing, a high quality starting material ($\tau$ of 5 ms bulk lifetime) has been used in the simulation. The thickness of this substrate is smaller than the substrate thickness considered in Ref. (Jeyakumar et al., 2013), where the thickness was 250 μm. The thinner wafer decreases the probability of recombination of electrons and holes as they travel across the bulk from near the front surface to the respective electrodes on the back. This clearly comes at a cost of a decrease in photon absorption, and consequently electron–hole pair generation (i.e. reduction in c-Si wafer thickness limit current density). In the BHJ structure, doped emitter/back surface field size was reported to be as high as 1.2 mm (Lu et al., 2007, 2011).

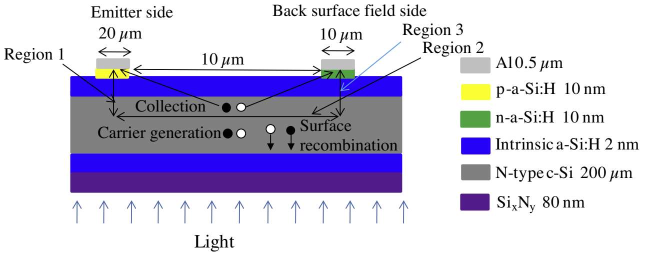

Fig. 1. Schematic cross-sectional diagram of c-Si based back heterojunction (a-Si:H/c-Si) solar cell (distance and size are not to scale). To lower the series resistance and to collect all the current, thick metal lines are required.

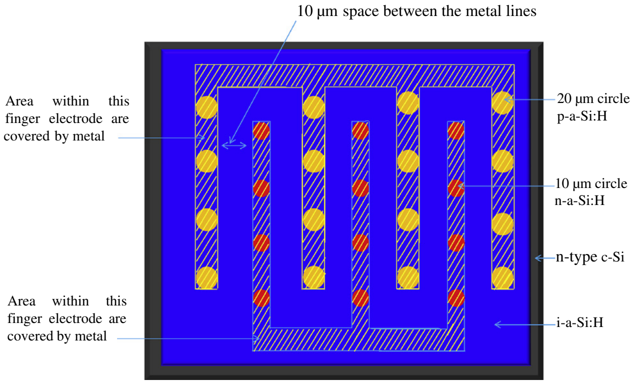

Fig. 2. Illustration of rear side layout of the back heterojunction (a-Si:H/c-Si) solar cell. Here p-a-Si:H and n-a-Si:H doped areas are shown as colored circles having diameter of 20 μm and 10 μm respectively.

In our point contact BHJ structure, to reduce recombination at the metal/semiconductor contact, doped areas were kept between 10 and 20 μm in diameter. To improve holes collection, back surface field size was kept lower than the emitter size. A 2 nm intrinsic a-Si:H buffer layer was added to both sides of the substrate for surface passivation. The grid less untextured front side, where light enters the cell, was covered with 80 nm thick silicon nitride ($Si_xN_y$) layer as an antireflection coating. On the rear side, for junction formation and carrier collection, heavily doped (for p-type $1.0 \times 10^{19}\ \text{cm}^{-3}$ and for n-type $2.0 \times 10^{19}\ \text{cm}^{-3}$) alternating p-a-Si:H (emitter) and n-a-Si:H (back surface field, or BSF), each with a thickness of 10 nm and a circular diameter of 20 μm and 10 μm respectively, and touching the metal layer, were considered. The space between the metal lines was kept constant at 10 μm. As a side note, 2 μm spacing between metal lines has been reported (Lu et al., 2007). The BSF region has a diameter of 10 μm, which, to our knowledge, is the smallest considered so far for Si based BHJ solar cell. One advantage is that this reduces the number of defects at the metal/doped a-Si:H interface since there is no passivation (intrinsic a-Si:H) at the interface.

For our study we utilized Silvaco Atlas tools (ATLAS, 2008) to study carrier generation-recombination, mid-gap traps, and photogeneration rate (by ray tracing) in BHJ cell structures. Tracing algorithm, i.e. ray-tracing program, has been used to trace individual light rays through the cell until they leave the solar cell or absorbed. Light-trapping was not considered in our simulation studies since no texturing was considered, and we used all material layers to study electrical properties in different regions of the device.

Simulations were performed by solving Poisson's equation and continuity equations for electrons and holes simultaneously (Diouf et al., 2010a; Lu et al., 2011). Drift–diffusion model was used to solve continuity equations for electrons and holes. Shockley–Read–Hall (SRH) recombination model, i.e. trap-assisted recombination