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Parametric simulation of the back-surface field effect in the silicon solar cell

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ABSTRACT

Recombination of minority carriers in the solar cell is a major contributing factor in the loss of quantum efficiency and cell power. While the surface recombination is dealt with by depositing a passivation layer of SiO_2 or SiN_x, the bulk recombination is minimized by use of nearly defect-free monocrystalline substrate. In addition, the back-surface field (BSF) effect has been very useful in aiding the separation of free electrons and holes in the bulk. In this study, the key BSF parameters and their effect on the performance of a typical p-type front-lit Si solar cell are investigated by use of Medici, a 2-dimensional device simulator. Of the parameters, the doping concentration of the BSF layer is found to be most significant. That is, for a p-type substrate of 1×10^{14} cm^{-3} acceptor concentration, the optimum doping concentration of the BSF layer is 1×10^{18} cm^{-3} or more, and the maximum cell power can be increased by 24%, i.e., 25.4 mW cm^{-2} vs. 20.5 mW cm^{-2}, by using a BSF layer with optimum doping. With regards to the BSF layer thickness, the impact is less. That is, the maximum cell power is about 11% higher at 100 μm than at 5 μm, which translates to an increase of 1.2% μm^{-1}. In practice, therefore, it would be better to rely on the control of the doping concentration than the thickness in maximizing the BSF effect in real Si solar cells.

1. Introduction

Not all the photons arriving at the surface of a solar cell are converted into electricity. Some are at first reflected back at the surface. Of the photons that enter into the body of the solar cell, those with energy less than the bandgap energy of silicon are transmitted through the back surface without being absorbed, and those with energy equal to or greater than the bandgap energy are absorbed and create an electron–hole pair, a pair for each photon. The photon energy in excess of what is required for an electron–hole pair creation is not normally reused but lost as heat. This thermal loss accounts a huge portion in case of the high-energy photons, corresponding to blue, violet and ultra violet radiations. As the result, the energy of the photons that are directly responsible for electron–hole generation accounts for less than 30%, in case of the Si solar cell, of the total energy of the incoming photons [1]. The electric fields at the pn junction separate the electron–hole pairs. The electrons or holes then flow out of the solar cell and pass through the load. The recombination of electrons and holes in the bulk, at the surface or the semiconductor–metal junctions before they reach the load will limit the internal quantum efficiency and result in the reduction of the electrical power and energy. As the result, the highest efficiency reported to date for an actual cell is 24.7% by a method known as PERL (Passivated Emitter, Rear Locally-diffused) [2]. More typical value accepted in laboratory-scale solar cells is about 20%, or 20 mW cm^2 under AM1.5 [3].

The electron–hole separation depends on how easy electrons and holes diffuse away from each other. Any imperfection would inhibit diffusion and cause a premature recombination of electrons and holes. The defects in the bulk of the silicon solar cell can be reduced to minimum by use of a float-zone or Czochralski monocrystalline silicon substrate. Defects on the front and back surface are normally passivated by depositing silicon dioxide or silicon nitride. The series resistance associated with the semiconductor–metal junctions is minimized by forming ohmic contacts at the junction. The electric field that enables the electron–hole separation is strongest at the pn junction near the front surface. Near the back surface, which is far away from the front pn junction, the field is weak to the extent that the electrons and holes are not easily separated. A BSF (Back-Surface Field) in the rear surface region, which creates energy-band bending that aids in the separation of electrons and holes, is known to be very useful in giving the extra push needed for electron–hole separation in this remote region.

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A BSF is formed by creating a heavily-doped p^+-type layer next to the p-type bulk at the back surface. The energy of the valence and conduction electrons becomes larger as the acceptor doping level, or the concentration of holes, gets larger. As such, at the p/p^+ junction, the energy band curbs upward towards the p^+ side. The resulting electrical field, the BSF, repels electrons towards the bulk and pulls holes into the BSF region. This enables more efficient separation of electrons and holes near the back surface, which results in reduced electron–hole recombination and overall increase in the quantum efficiency. A more detailed analysis in terms of the physical mechanisms effective in the BSF Si solar cell and concise analytical descriptions of the cell performance is given by J.G. Fossum [4].

In practice, the BSF layer is typically formed during metallization of the back surface. That is, screen-printed aluminum paste is applied to the back surface of the solar cell and fired at 700–900 °C in order to form the back electrode. In this firing process, aluminum diffuses into Si and forms a passivating p^+-Si layer called the aluminum back surface field (Al-BSF) [5]. Due to this simple fabrication process, the Al-BSF cell structure is low-cost and high-throughput in nature and thus widely used in the industry. However, thermal expansion mismatch between Al and Si may result in warping of wafers if wafers are too thin [6], as well as the efficiency of commercial Al-BSF cells has plateaued at about 19% due to relatively high rear recombination losses and parasitic light absorption associated with the Al-BSF [7,8]. For more efficient solar cells, such as the above mentioned PERL, boron back-surface field (B-BSF) is utilized instead, though this requires an additional boron diffusion step.

Besides the BSF, though not covered in this study, a selective emitter configuration may also be used to improve the cell efficiency. That is, the emitter on the front surface is divided into a lightly-doped layer that makes contact with the base (substrate) and heavily doped localized regions just underneath the top metal contacts. By limiting the heavily doped regions to just near the metal contacts, Auger recombination that is positively related to the doping level can be significantly reduced without greatly increasing the contact resistance, thus resulting in the overall improvement in the cell efficiency [9].

The experimental data reported to date generally support the above-stated notion that the BSF aids in the separation of electrons and holes. However, the basic parameters of the BSF layer, namely the thickness and the doping concentration, and their relation to the quantum efficiency are yet to be investigated comprehensively. In this work, Medici, a 2-dimensional semiconductor device simulation tool, is utilized in the investigation. Despite simplifications, the simulation results should corroborate the experimentally proven benefits of the BSF. It is hoped that the detailed parametric analysis yields the optimum dimension and doping concentration of the BSF layer.

2. Experimental

In situations that call for repeated experiments with incremental changes in a variable or variables, numerical modeling and simulation can be a useful substitute. It is a tool that can not only save time and money, but also single out and examine the variable in interest while keeping other factors and variables essentially constant. In concept, the numerical modeling and simulation of an electronic device is analogous to building a modeled house, ship or airplane, which is next to the real thing. Essential features of a real house, ship or airplane can be formed, viewed and tested in a modeled structure before the actual structure is built at great expense and time. In numerical modeling and simulation, all these are done in the virtual space.

The Medici simulation consists of four major steps. First, the solar cell structure is formed by grids or meshes, a sort of like building a modeled house using match sticks. The regions near the front and back surfaces and at the pn junction where active photogeneration and carrier recombination occur are finely meshed, and the bulk region deep in the body of the solar cell, where the electrical activities are relatively minor, are coarsely meshed to save computation time. Each type of the n- and p-type regions is then doped to a desired level. Second, the physical models relating to the operation of the solar cell and mathematical models and methods relating to the numerical simulation are each specified. Third, the solutions are reached by iterative numerical simulation. Fourth, the simulation results or the outputs are accessed in text, graphic or pictorial format.

The solar cell chosen for the simulation study is a front-lit structure of p-type silicon substrate. A standard back-lit grid structure in the Medici operational manual [10] is modified to meet the front-lit structural requirements. In this 2-dimensional front-lit structure, the substrate is 150μm in thickness and doped p-type in the concentration of 1×10^{14} cm^{-3}. Laterally, only a 10 μm segment of the substrate is chosen to conserve the simulation time. The n-type emitter on top is doped to the concentration of 1×10^{17} cm^{-3}. The location of the pn junction, between the emitter and the base (substrate), is 2 μm below the front surface. A front metal contact finger is placed in the middle of the modeled structure and 1 μm in width. The back metal contact covers the full area of the back surface. This structure was tested and used as a reference in comparison to back-lit solar cells in an earlier work [11].

In regards to model and parameter selection, Auger and concentration-dependent Shockley-Read-Hall recombination models and a concentration-dependent mobility model are chosen. The 2-carrier Newtonian iteration is chosen as the mathematical method in solving the governing equations by finite element analysis. The minority carrier lifetime of 5×10^{-5} sec is assigned for both electrons and holes. Lastly, except for the parameters that are chosen, default values are used.

The photogeneration rate, electron-hole-pairs·cm^{-3} s^{-1}, is an exponential function of distance y from the surface and can be expressed as

$$G_{\text{photon}} = \text{FLUX}\frac{\exp\left[\frac{-y}{\text{Y.CHAR}}\right]}{10^{-4} \times \text{Y.CHAR}} \tag{2.1}$$

where FLUX is defined as the photon flux (photons·cm^{-2} s^{-1}) and Y.CHAR is defined as the absorption distance (μm) [10]. The photon absorption is strongly frequency-dependent. That is, higher the frequency, or shorter the wavelength, the stronger the photon absorption and therefore the shorter the absorption distance. For the present simulation experiments, the wavelength of 0.6 μm (600 nm), the peak point in the AM1.5 spectrum having an absorption distance of 2 μm, is chosen for the incident photons. The photon flux is set at 4×10^{17} cm^{-2} s^{-1}. For these absorption distance and photon flux, the Eq. (2.1) can be rewritten as

$$G_{\text{photon}} = 2 \times 10^{21} e^{\frac{-y}{2\ \mu\text{m}}}\ cm^{-3}\ s^{-1} \tag{2.2}$$

Finally, after the simulation, the output is plotted in terms of the photovoltaic equation as expressed in

$$I = I_o\left(e^{\frac{qV}{kT}} - 1\right) - I_{sc} \tag{2.3}$$

From the I–V curve plotted, the open-circuit voltage, V_{oc}, is extracted from where the curve intersects the x-axis, and the short-circuit current, I_{sc}, is extracted from where the curve intersects the