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Simulation and Optimization of Single Silicon Nanowire Solar Cell with Radial Junctions

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Abstract

In recent years, both solar cell research and nanowire research have become popular topics in design and fabrication of semiconductor devices. The need for higher solar cell efficiencies at lower cost has been the main concern of scientists and engineers. Nanowire solar cell is one candidate for decreasing the cost of solar cell fabrication. The nanowire geometry has many advantages over planar bulk and thin-film solar cells in processes of photoconversion. They reduce the quantity and quality of material necessary to obtain the limits, which leads to lower cost. In addition, complex single-crystalline nanowires are able to be fabricated directly on low-cost substrates and electrodes. In this work, we simulate single vertical nanowire solar cell made from silicon with radial junction, in order to examine the influence of the different parameters of the cell structure on efficiency. Length and diameter of the cell, thicknesses of regions, dopant type and concentration are these parameters. The simulations enable one to find the optimized structure and predict the fabrication process.

Keywords: *: Nanowire solar cell, Core-shell nanowire, Radial junction, N-p structure, N-i-p structure.*

1. Introduction

Solar energy harvest has attracted much attention in the previous decades. The need for higher solar cell efficiencies at lower cost has become apparent, and at the same time synthetic control in nanoscience has improved such that high-performance electronic devices are becoming possible (Cao et al., 2010; Gunawan et al., 2008; Ford et al., 2009). In recent years, Nanowire solar cells have been investigated for improving optical absorption (Adachi et al., 2010; Li et al., 2009; Lin and Povinelli, 2011; Sivakov et al., 2009; Tsakalakos et al., 2007;) , collection efficiency (Garnett and Yang, 2010; Law et al., 2005) and some other potential benefits over traditional wafer-based or thin-film devices related to optical, electrical, and strain relaxation effects. Bottom up grown nanowires, usually by the vapor-liquid-solid (VLS) method, offer a simple and large area compatible method for synthesizing a dense array of silicon nanowires on low cost glass substrates (Adachi et al., 2013). Ordered arrays of vertical nanowires with radial junctions take advantage of all mentioned effects, although solar cells made using axial junctions or random arrays can still have some benefits over planar cells (Garnett et al., 2011). Nanowire photovoltaic devices have been fabricated using variety of materials including silicon, germanium, zinc oxide, zinc sulfide, cadmium telluride, cadmium selenide, copper oxide, titanium oxide, gallium nitride, indium gallium nitride, gallium arsenide, indium arsenide, and many polymer/nanowire combinations (Fan et al., 2009; Greene et al., 2007; Varghese et al., 2009; Wang et al., 2011; Wei et al., 2009; Yuhas et al., 2009; Williams et al., 2008)

In this paper, we simulate a radial junction silicon nanowire in order to investigate the effects of length and diameter, doping type and concentration and thickness of each region, on output parameters. At first step, we study the influence of length and diameter of the nanowire cell. Secondly, the thickness of each region in p-n junction and p-i-n are taken into consideration. The thicknesses of p-type, n-type and intrinsic layers have impacts on charge separation and consequently on photoconversion due to difference in electric field distribution. The type of dopants for core and shell of the cell and also the concentration of them affect the diffusion length and amount of the charge reach the contacts. All these effects can be compared by examining the short circuit current, open circuit voltage and efficiency of the simulated cell.

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2. The Structure of Nanowire Solar Cell

A TCAD device simulator is exploited to analyze the influences of design parameters like doping concentrations and types, and thicknesses under AM1.5 solar spectrum. The structure of simulated cell is defined as a p-n or p-i-n radial junction with transparent contacts on top and bottom. Outside of the cell is coated and passivated by a silicon nitride layer. Fig 1. shows the defined structure for p-i-n junction cell.

Inner active layer and outer active layer can be either p-type or n-type silicon, with different doping concentrations and different thicknesses. The layer between them is an intrinsic layer which is eliminated in some cases to compare the effects of its existence and thickness with other cases. Numerical solutions are obtained by discretizing the cell structure in grid points whose spacing has to be short enough to follow microscopic variations of geometrical and electrical parameters. Once the geometries of the cell have been defined, material electrical properties, minority carriers recombination, doping concentrations, etc. are set to perform the simulations.

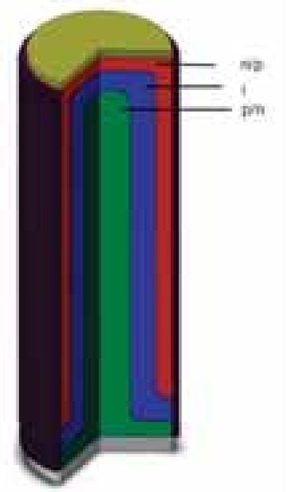

Fig. 1: The structure of nanowire solar cell

3. Simulation Results and Discussion

3.1. Effect of Nanowire Length

In first step, we simulate the nanowire structure for different lengths of the cell. By assuming constant diameter of 200nm and n-p junction with same thicknesses and doping concentration of $5\times10^{17}cm^{-3}$, the influence of cell length is taken into consideration. Open circuit voltage, short circuit current and the efficiency of the nanowire cell for different lengths are as in Table.1.

Table 1. Open circuit voltage, short circuit current and the efficiency of the nanowire cell for different lengths

Length (µm)	0.5	1	2	3	4
V_{OC} (V)	0.409	0.416	0.417	0.414	0.410
I_{SC} (pA)	2.44	3.64	5.02	5.88	6.50
Efficiency (%)	2.35	3.51	4.74	5.43	5.87

Increasing the length, results in more generation along the cell and due to improved collection efficiency of nanowires, short circuit current get higher values. Open circuit voltage is changed a little by changing the length, therefore maximum power of the cells almost occur in same voltages. In consequence, output power and the efficiency of the cell improve in longer cells.

3.2. Effect of Nanowire Diameter and Dopant Types

In order to study the impact of core and shell dopant types, we simulate the structure in four forms, and with different diameters to consider the thicknesses. N-type core, p-type shell and vice versa without intrinsic layer, and with intrinsic layer are these forms of structure. We assume that the layers in each case have the same thickness. For examining the influence of nanowire diameter on output parameters, the cell with four mentioned forms is simulated in different diameters. Fig.2 shows the efficiency of these four forms with different cell diameters.

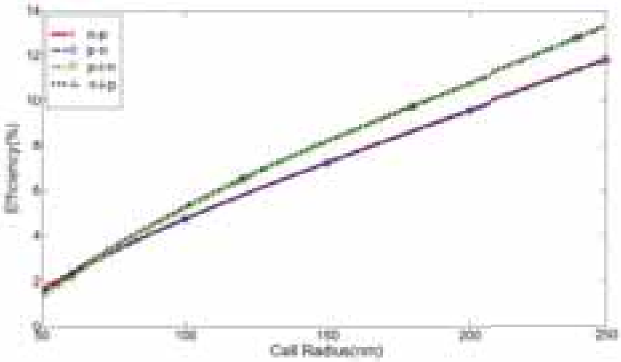

Fig. 2. The efficiency of different structure forms of nanowire solar cell with different lengths

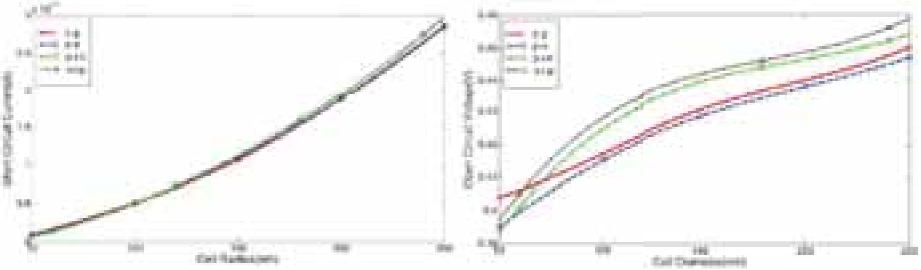

Fig. 3. (a) Short circuit current (b) Open circuit voltage, of different structure forms with different cell diameters.

It can be seen that in all cases, increasing the diameter improves the efficiency of the cell. These diameters are below the mean free path of the carriers, therefore almost all the generated carriers participate in the cell current. By increasing the area projected to solar light output power is increased due to higher level of photogenerated current and higher voltage. Fig.3.a and Fig.3.b show the short circuit current and open circuit voltage versus cell diameter.

It is shown that short circuit current changes almost proportionally to the area of the cells. But, longer diameter leads to higher open circuit and it will result in higher output power.

Another important phenomenon that should be taken into consideration is the difference between core and shell dopant type. Fig.2 shows that n-p junction (n-type core and p-type shell) has better efficiency than p-n junction cell. This improvement is not considerable and is due to difference in resistivity of the core and shell which also results in difference in open circuit voltage. This is also true for n-i-p in comparison with p-i-n structure.

Including an intrinsic layer in cell structure enhances the cell efficiency because electric field distributes in more positions across the nanowire and leads to higher voltages in constant diameters in comparison with structure with no intrinsic layer. Thus, open circuit voltage is also improves. Electric field distribution across the cell is shown in Fig.4.a and Fig.4.b for n-p and n-i-p structure.

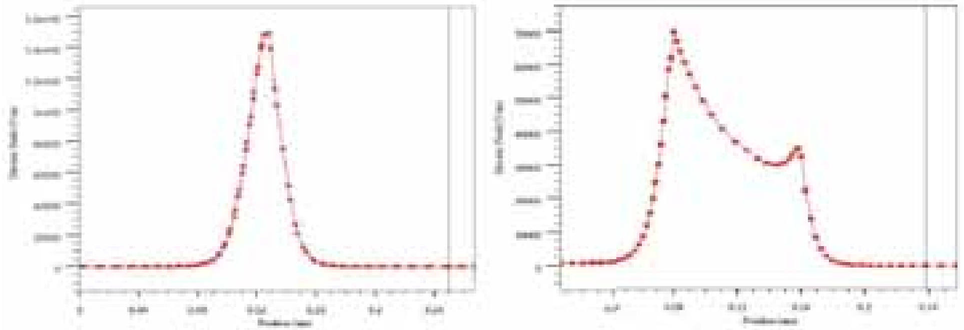

Fig. 4. Electric field along the radius of the cell, (a) p-n structure (b) p-i-n Structure

3.3. Effect of Active Layer Thicknesses

For next step, n-p and n-i-p junction cells are simulated with different active layer thicknesses. First, the n-p cell with radius of 100nm and then the n-i-p cell with radius of 120nm are studied. Fig.5.a and Fig.5.b show the efficiency of these structures respectively. In n-p cell the core radius is changed from 12.5nm to 87.5nm. In n-i-p cell, for three intrinsic thicknesses, the radius of the core is changed to investigate the efficiency.

It is depicted that by increasing the ratio of core thickness to cell thickness up to 0.6, the efficiency improves, but it reduces in higher ratios. This reduction is negligible in n-p structure. The thickness of intrinsic layer has different impacts on efficiency by changing the ratio. Thicker intrinsic layer raise the efficiency of the cell in middle ratios. But it causes reduction in efficiency in high and low ratios.

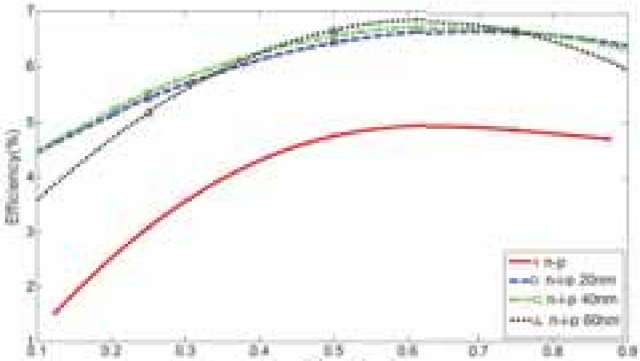

Fig. 5. The efficiency of n-p structure and n-i-p with different thicknesses of active layers

Fig.6.a shows the short circuit currents of both structures with variant core, shell and intrinsic layers' thicknesses and Fig.6.b shows their open circuit voltages.

It is seen that short circuit current increases when the ratio get higher values. The rate of this rise is higher in cell with thicker intrinsic layer. This is different for n-p structure in higher ratios. The intrinsic layer enhances the short circuit current in higher ratios. The open circuit voltage is determined by two parameters, the value of the electric field and the distance it distributes. In thinner intrinsic layer, in middle ratios, the value of electric field is higher and results in higher voltages. But while the ratio goes higher or lower, the distribution of electric field becomes the dominant parameter.

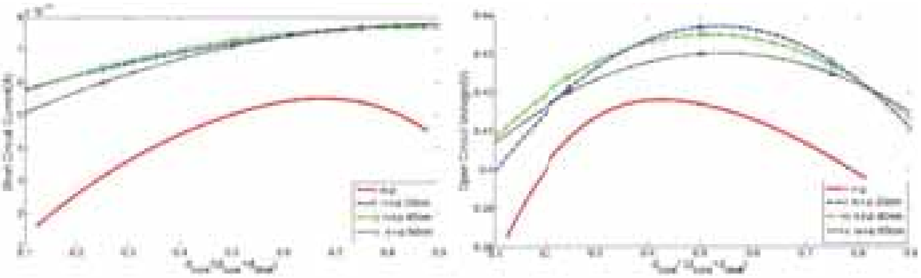

Fig. 6. (a) Short circuit current (b) Open circuit voltage of n-p structure and n-i-p with different thicknesses of active layers

3.4. Effect of Doping Concentration

Finally, the n-i-p structure with 40nm intrinsic layer, 20nm core and 60nm shell is simulated. The doping concentrations of both core and shell are changed in order to examine the efficiency, short circuit current and open circuit voltage. Fig.7 and Fig.8.a and Fig.8.b show these parameters.

It can be seen in Fig.7 that by increasing the doping concentration of both core and shell region, efficiency get higher values. The rate of increment reduces in higher concentrations. Short circuit current decreases because of more recombination in nanowire cell when doping concentration rises. But it enhances due to higher electric field especially near the junctions, thus different behaviors can be seen by changing the doping concentration in core and shell. Voltage changes by changing the electric field and in consequence it improves in higher levels of doping. By examining the Fig.8 it is confirmed that the efficiency in higher concentration of doping is higher because the voltage improves and the current does not change a lot. But in other concentration either current or voltage reduces considerably.

4. Conclusion

In this paper effective parameters of silicon nanowire solar cells' structure on efficiency are investigated by means of TCAD simulator. Length and diameter of the cell, thickness, type and doping concentration of p-type and n-type regions are studied. Longer and thicker cells have higher output powers and efficiencies.

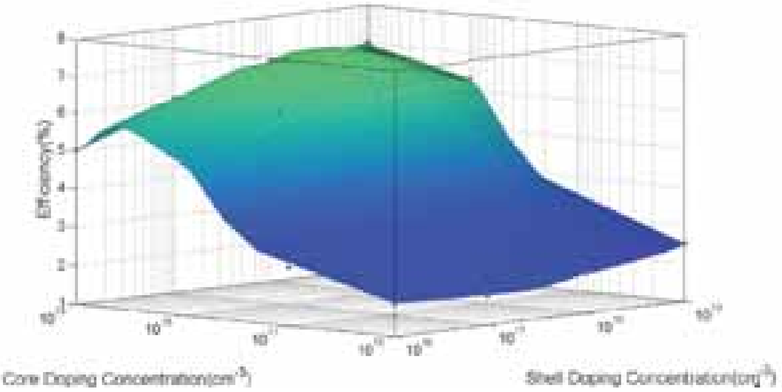

Fig. 7. The efficiency of the cell in different core and shell doping concentrations

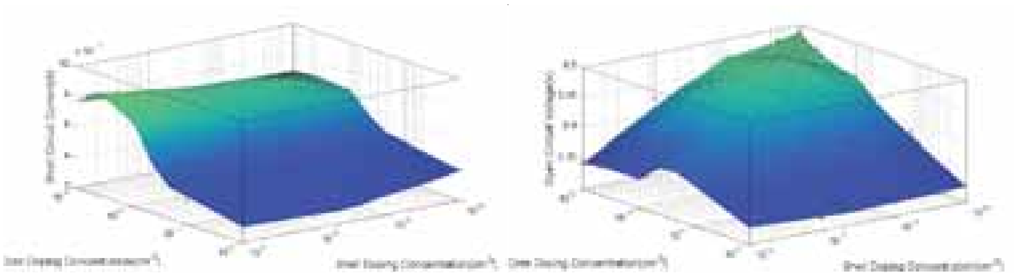

Fig. 8. (a) Short circuit current (b) Open circuit voltage of the cell with different core and shell doping concentrations

It is seen that n-p and n-i-p structures show better performance in comparison with p-n and p-i-n. Including an intrinsic layer in cell structure enhance the efficiency and in consequence, n-i-p structure shows the highest efficiency among the structures. For optimizing the thicknesses and doping concentrations different simulations are done. In different thicknesses the optimized structure is varied, it can be said that the efficiency of the cell with thicker intrinsic layer and core region got higher values. Increasing the doping concentration of the cell regions improve the efficiency. These analyzes will help one to optimize the structure of silicon nanowire solar cells before fabrication. By simulating all effects, generalizing and obtaining analytic relations from fitted curves, exact rules can be reached for predicting the optimized structures.

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