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Study of the influence of doping and layer thickness on the efficiency of ZnO/porous-Si/Si photoconverters

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Abstract. The article investigates the effect of doping and layer thickness on the efficiency of solar cells based on the ZnO/porous-Si/Si heterojunction using PC1D simulation. The results show that optimizing the ZnO and porous-Si layers' thickness significantly affects the solar cell's performance. The maximum current value was achieved at a ZnO thickness of 10 μm and porous-Si of 1 μm. In comparison, with an increase in the thickness to 15 μm, the material approaches the bulk, which reduces the efficiency due to increased carrier recombination. A significant effect of the doping concentration of the ZnO film was found. When the doping concentration increased to 10^{19} cm^{-3}, the highest efficiency was achieved – 22.6%. However, excessive doping causes increased carrier recombination, which leads to a decrease in cell performance.

1 Introduction

One of the key areas of development of modern renewable energy is increasing the efficiency of solar cells (SC) [1, 2]. An effective method of improving the cells is to optimize their structure. Since changing any stage of the production process is a complex and expensive task, more and more attention is paid to modeling. Modeling allows you to quickly test different design options without the need to build physical prototypes. A tool that has recently been widely used for modeling solar cells is the PC1D software, which allows you to analyze the operation of semiconductor devices based on physical models [3, 4].

An important aspect of modeling is the ability to study the influence of parameters such as doping and thickness of the active layers of photoconverters. Doping the active layers of photoconverters allows you to change the concentration of charge carriers, which directly affects the conductivity and other electrical properties of the material. The thickness of the layers determines the efficiency of solar radiation absorption, and also affects the generation and recombination of charge carriers. The ability to control the doping and thickness of the layers allows you to achieve a better balance between minimizing energy losses and increasing the number of charge carriers that are converted into electric current. This is especially important in the context of the growing demand for more economical and high-performance solar energy conversion technologies, where every percent increase in

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efficiency has a significant impact on the overall performance of the system. Thus, modeling helps to fine-tune the design of solar cells to maximize the use of available energy and reduce production costs.

Modern research aimed at improving the efficiency of solar cells, in particular through optimization of the thickness of the active layer [5] and the use of various dopants [6], focuses on studying the effect of doping on the performance of solar cells, optimizing the thickness of the active layer, modeling and selection of optimal modeling methods, etc. A study of the effect of the thickness and doping concentration of the n-layer of silicon solar cells using PC1D modeling [7] showed that optimizing these parameters allows achieving high efficiency (87.71%) and can be used to produce high-efficiency monocrystalline solar cells.

Controlled doping reduces recombination losses and increases the concentration of charge carriers, which improves the efficiency of solar energy conversion. The use of dopants significantly increases the stability and performance of photovoltaic cells. For example, the study [8] analyzes the effect of doping technologies on increasing the theoretical efficiency of crystalline silicon.

Reducing the thickness reduces material costs and light absorption losses, but excessive reduction in thickness can lead to losses due to recombination of charge carriers on the surface. Yu & Fan in [9] consider the role of a thin silicon layer in light capture and reducing recombination losses, and in [10] analyze the effect of layer thickness on the characteristics of heterojunctions in solar cells.

A significant increase in the efficiency of light conversion due to improved absorption and reduced recombination losses has been achieved recently through the use of nanostructured materials, including porous silicon porous-Si. We have previously investigated heterostructures based on porous silicon [11-13].

The combination of silicon with zinc oxide is quite promising [14-15]. In the study [16] and others, the use of zinc oxide ZnO as a transparent electrode with high conductivity and low absorption is discussed, which makes it effective for heterojunctions with silicon. ZnO deposited on porous silicon allows for improved electron collection and better interaction between different layers of the element [17].

Porous silicon as a buffer layer performs several important functions, in particular, it improves surface passivation, reduces the effects of charge carrier recombination, and increases light absorption due to its nanostructure [18], which allows to improve the properties of the heterojunction significantly.

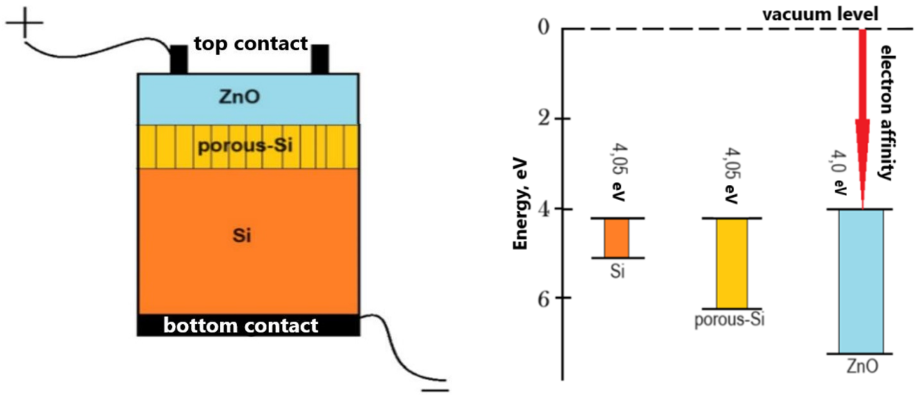
Although the ZnO/porous-Si/Si heterostructure and its application in solar energy are not new, the issues of optimizing the structure of porous silicon, modeling the photovoltaic properties of the heterostructure using software, etc., are still insufficiently studied.

The aim of this work is to investigate the effects of doping and thickness on solar cell efficiency using PC1D simulations. The results of the study will help to better understand how changes in these parameters can improve the efficiency of photovoltaic devices, and will also contribute to the development of more efficient solar cells in the future.

2 Presentation of the main material

The study focused on factors such as thickness and doping concentration to study their influence on the I-V characteristics of the ZnO/porous-Si/Si photoconverter, other main parameters were fixed. For numerical simulation, the initial physical parameters of ZnO, porous-Si and Si, given in [19], were used. Although the electrical energy generation and performance require consideration of all parameters, for simplification and understanding of the influence of parameters, some factors will be fixed.

A schematic representation and energy band diagram of the ZnO/porous-Si/Si solar cell, in which the ZnO layer is used as the ARC and the window layer, are shown in Fig. 1 (a, b).



a b

Fig. 1. Schematic representation (a) and band energy diagram (b) of a ZnO/porous-Si/Si heterojunction solar cell.

The I-V characteristics were obtained with the thicknesses of the ZnO and porous-Si layers in the range of 1-10 µm, the maximum current strength was achieved at d_{ZnO}=10 µm, $d_{porous\text{-}Si}$=1 µm, and the minimum at d_{ZnO}=1 µm, $d_{porous\text{-}Si}$=10 µm (Table 1). The effect of layer thickness on the I–V characteristic ceases at d=15 µm, as the material becomes bulk, so that the recombination carrier decreases.

Table 1. Current strength of the ZnO/porous-Si/Si heterojunction solar cell at different layer thicknesses.

Layer thickness, µm										
ZnO	**porous-Si**									
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
	Amperage, mA									
1	40.9	40.7	40.6	40.5	40.3	40.2	40.4	39.9	39.8	39.7
2	40.9	40.8	40.7	40.6	40.5	40.4	40.2	40.1	40.0	39.9
3	40.9	40.9	40.8	40.7	40.6	40.5	40.4	40.2	40.1	40.0
4	40.9	40.9	40.8	40.7	40.6	40.5	40.4	40.3	40.2	40.2
5	40.9	40.9	40.8	40.8	40.7	40.6	40.5	40.4	40.3	40.2
6	41.0	40.9	40.9	40.8	40.7	40.7	40.6	40.5	40.4	40.3
7	41.0	40.9	40.9	40.8	40.8	40.7	40.6	40.5	40.5	40.4
8	41.0	40.9	40.9	40.8	40.8	40.7	40.7	40.6	40.5	40.4
9	41.0	40.9	40.9	40.9	40.8	40.8	40.7	40.6	40.6	40.5
10	41.0	41.0	40.9	40.9	40.8	40.8	40.7	40.7	40.6	40.5

Most of the light is absorbed close to the surface. By making the front layer very thin, a large fraction of the carriers generated by the incoming light are created within the diffusion length of the p-n junction. The open circuit voltage showed approximately 711.7 mV, the efficiency was 22.6%, the I-V characteristic is presented in Fig. 2.

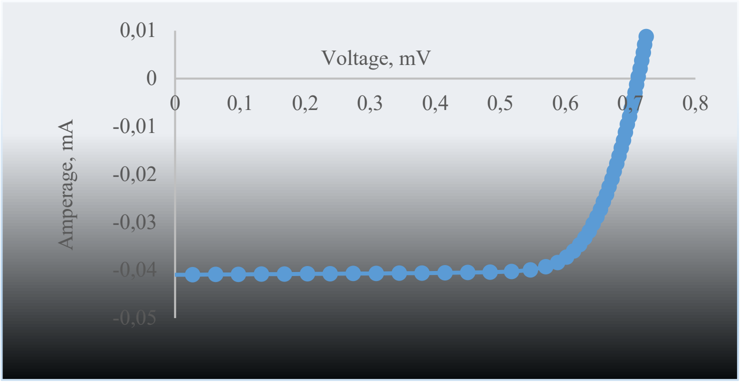


Fig. 2. I–V characteristics of the ZnO/porous-Si/Si photoconverter.

To determine the optimal doping concentration and its effect on efficiency, the doping concentration of the ZnO layers was varied, while the concentration of Si and porous-Si was kept constant at 10^{16} cm^{-3}. The dependence of efficiency on the doping level is presented in Fig. 3.

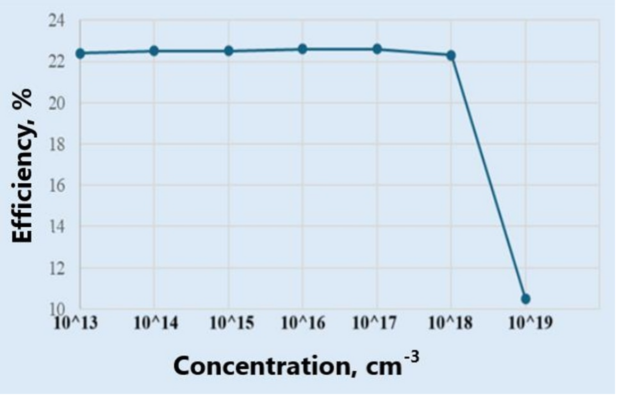


Fig. 3. Dependence of the efficiency of the ZnO/porous-Si/Si photoconverter on the doping level of the ZnO layer.

The doping concentration increases continuously from 10^{13} to 10^{19} cm^{-3}, the current and voltage also gradually increase. The highest values were achieved at a doping of 10^{19} cm^{-3}, namely 41.0 mA, 710.8 mV and 22.6%. It can be seen from Fig. 3 that excessive doping degrades the quality of the material to the point that the carriers recombine before reaching the junction. That is, higher doping concentrations lead to an increase in carrier recombination or a decrease in the lifetime of minority carriers [7].

3 Conclusions

The study of the influence of layer thickness and doping concentration on the efficiency of solar cells based on ZnO/porous-Si/Si heterojunction showed that optimization of these parameters allows achieving high efficiency. The maximum efficiency was 22.6% at optimal thickness and doping values. However, excessive doping can negatively affect the quality of the material, which emphasizes the importance of choosing the right parameters to achieve maximum performance. The results obtained can be used to develop more efficient solar cells in the future.

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