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Suns-V_{oc} Characteristics of Silicon Solar Cell: Experimental and Simulation Study

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The efficiency of solar cells depends on the quality of passivation of surface. The quality of passivation is analyzed as a function of the dependence of the open circuit voltage on the light intensity. Therefore, in this article, the dependence of the photoelectric parameters of the silicon-based solar cell on the light intensity was studied. According to the obtained results, it was found that the variation of the short-circuit current through light intensity is equal to 25.6 mA/suns·cm^2. The agreement of the results obtained in research and modeling with the results of experiments proves the validity and correctness of the model. In this paper, the Sentaurus TCAD model of a silicon-based solar cell is experimentally verified. So, the dependence of the open circuit voltage of the silicon-based solar cell on the light intensity was studied through modeling and experiment. The functional dependence of the open circuit voltage obtained in the modeling satisfied the experiment. Therefore, the model of the solar cell created in Sentaurus TCAD is suitable for research. So, we can use model created in Sentaurus TCAD in our further researches. In addition, the fill factor of solar cell increased with increasing intensity. This proves that the resistive properties of the solar cell are improving.

Keywords: Solar cell, Simulation, Open circuit voltage, Photoelectric parameters, Passivation.

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1. INTRODUCTION

Today, meeting the need for electricity with renewable energy sources is one of the urgent issues. There are many types of renewable energy sources. Most important of them is solar energy. A device that converts light energy from the sun into electrical energy is called a solar cell. In industry mainly silicon-based solar cells are produced [1]. Electricity from solar cells accounts for 3.9 % of the electricity produced in the world [2]. Due to the low efficiency and high cost of solar cells, they are not widely used. For example, the efficiency of an industrial silicon-based solar cell is 23.46 % [3]. There are 3 main types of losses in solar cells [4]: optical [5], electrical [6] and thermal [7]. Optical losses include spectral mismatch, reflection, and parasitic absorption. To reduce spectral mismatch, the surface of the solar cell is coated with luminescent materials [8]. Luminescent (down-shifting) materials can absorb high-energy photons and emit lower-energy photons. Also, some luminescent (up-conversion) [9] materials absorb lower-energy photons and emit high-energy photons. Since the bandgap of silicon is 1.12 eV, silicon-based solar cells mainly absorb light in the visible spectrum [10]. It almost does not absorb light in infrared spectrum. In order to increase the absorption of a silicon-based solar cell in infrared spectrum, its surface should be coated with upconversion luminescent materials [11]. To reduce the reflection of the incident light on the solar cell, its surface should be covered with an anti-reflection layer [12] and formed various textures [13]. When a high-energy photon is absorbed in silicon, a high-energy electron is generated. A high-energy electron is unstable and quickly recombines. The energy generated during recombination causes heating of the crystal lattice. To reduce this parasitic absorption, a silicon-based solar cell must be coated with downshifting luminescent materials [14]. In the back contact of solar cells, infrared lights are well absorbed. Therefore, the temperature of the solar cell increases rapidly. To prevent heating of the solar cell, its back contact should be made in the form of a grid.

Due to the dangling bonds on the silicon surface, the amount of recombination is high [15]. Surface recombination is reduced by coating with a passivation material. In silicon-based solar cells, mainly use SiN_x and SiO_2 are used as passivating materials [16]. The quality of the surface of the solar cell affects its parameters. It is possible to analyze the passivation quality of the surface of the solar cell using the function of the dependence of the open circuit voltage on the light intensity. Therefore, in this article, the dependence of the open circuit voltage of a silicon-based solar cell on the light intensity was studied by simulation and experiment. Second aim of this work is comparison of simulation results with experiment. It helps to verify validation of model created in Sentaurus TCAD.

2. MATERIALS AND METHOD

2.1 Experiment

The relationship between open circuit voltage and light intensity was measured on a Sinton Suns-V_{oc} device. Since Sinton Suns-V_{oc} is an automated device, its measurement accuracy is high. The device has a xenon lamp, and its intensity changes from 3.6 suns to 0.01 suns solar intensity in 13 ms, as shown in Fig. 1. The maximum intensity can be increased to 6 suns by changing the height of the lamp. During 13 ms, the device measures the open circuit voltage of different intensities. The obtained results are saved in the form of data in the control software of the Sinton Suns-V_{oc} device. To analyze the results, Sinton Suns-V_{oc} software uses two different methods: Generalized and QSS (Quasi-steady-state) photoconductivity. Generalized method is mainly

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used for silicon solar cells and QSS method for non-silicon solar cells. Since our sample is a silicon-based solar cell, we used the generalized method to analyze the obtained results.

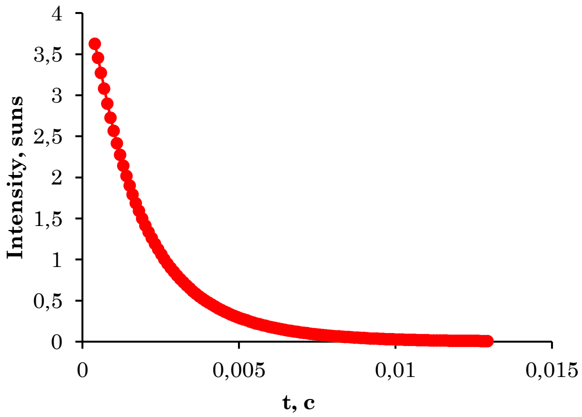

Fig. 1 – Variation of light intensity of Suns-V_{oc} device during relaxation time

Emitter and base thicknesses of the sample are 175 µm and 1 µm, respectively. The relaxation time of the light should be selected according to the thickness of the sample. If the thickness of the sample is less than 300 µm, the relaxation time should be 13 mc. Therefore, in the graph given in Fig. 1, the relaxation time of the lamp is 13 mc. 1×17 cm^{-3} Phosphorus atoms and 1×15 cm^{-3} Boron atoms were doped into the emitter layer and base of the sample. In order to accurately measure the *I-V* characteristic using the Suns-V_{oc} device, the short-circuit current density must be entered correctly. The short-circuit current density of the sample was measured using an ammeter. The surface of the sample is coated with 100 nm thick SiN_x as an anti-reflective and passivation layer. Front and rear contacts are made of aluminum. In addition, the resistivity of the base is 2 Ohm × cm.

2.2 Simulation

Today, various programs have been developed to simulate the solar cells in 1D, 2D and 3D dimensions. For 1D simulation, PC1D [17], SCAPS-1D [18] and AMPS-1D [19] are available. Sentaurus TCAD [20], Silvaco TCAD [21] and Lumerical TCAD [22] are widely used to simulate solar cells in 2D and 3D dimensions. In this paper, Sentaurus TCAD software was used to simulate the solar cell. Sentaurus TCAD has 23 main instruments. Four of them were used to model the solar cells: Sentaurus Structure Editor, Sentaurus Device, Sentaurus Visual and Sentaurus Workbench. A geometric model of the solar cell is created in the Sentaurust Structure Editor. The material type, doping concentration and type of each layer are given. In addition, since the calculation was carried out using a numerical method, the solar cell was meshed in the required dimensions. The *p-n* junction and contact areas are meshed in smaller sizes, and the overall structure is meshed in larger sizes. Because the *p-n* junction and contact areas are active, there will be many physical processes. Solar cells are simulated in 2D because of their symmetry. The thickness and doping concentration were taken to be the same as those of the sample used in the experiment. The general structure was meshed with a size of 1 µm and active areas with a size of 0.2 µm. After the geometric model is developed, the physical parameters of the necessary materials are given in Sentaurus Device. The photoelectric parameters of the solar cell are strongly depended on the light spectrum. Therefore, a light spectrum close to the solar spectrum should be selected. In this scientific work, AM1.5G was used as the light spectrum. Solar cells are simulated based on fundamental theories of optics and semiconductor physics.

When light fall on the boundary between two mediums, it reflects and refracts. The angular distribution between the incident, reflected and refracted rays at the boundary of two mediums is calculated by Snell's law, and the energy distribution is calculated by the Fresnel formulas given in formula 1.

$$\begin{cases} r_t = \dfrac{n_1 \cos\beta - n_2 \cos\gamma}{n_1 \cos\beta + n_2 \cos\gamma} \\ t_t = \dfrac{2n_1 \cos\beta}{n_1 \cos\beta + n_2 \cos\gamma} \end{cases} \quad \begin{cases} r_p = \dfrac{n_1 \cos\gamma - n_2 \cos\beta}{n_1 \cos\gamma + n_2 \cos\beta} \\ t_p = \dfrac{2n_1 \cos\beta}{n_2 \cos\beta + n_1 \cos\gamma} \end{cases} \tag{1}$$

Here: r_t and t_t are the Fresnel coefficients for transversal polarized light, r_p and t_p are the Fresnel coefficients for parallel polarized light, n_1 and n_2 are the refractive indices of first and second media, β is the angle of incident light, γ is the angle of refracted light.

Light is absorbed when it passes through the medium. The amount of light absorption is calculated using the Burger-Lambert law given in formula 2, depending on the optical properties of the medium and its thickness.

$$G^{opt}(x,y,z,t) = I(x,y,z,t)\left[1 - e^{-\alpha L}\right] \tag{2}$$

Here: G_{opt} is optical generation, I is light intensity, L is medium thickness, x, y, z are Cartesian coordinates, t is time, α is absorption coefficient of medium.

Since the solar cell is a complex optical system, light absorption, reflection and transmission cannot be calculated only by Fresnel or Burger-Lambert law. Therefore, we need a more perfect model for optical simulation. To calculate the optical properties of solar cells, Sentaurus TCAD mainly uses 3 models [23]: Transfer Matrix Method (TMM), Ray Tracing and Beam Propagation. In this paper, we used TMM for optical simulation. Because TMM takes into account the surface roughness of the solar cell and the internal interference in the layers. After determining the light absorption coefficient of the solar cell, the electron-hole generation is calculated using the quantum yield function. The quantum yield function is a logical function. If the absorbed photon energy is greater than the bandgap of the material, the quantum yield function is equal to 1, otherwise it is equal to 0. Electrons belong to the fermions and follow the Fermi-Dirac distribution. Therefore, the electron and hole concentrations are calculated using the Fermi function given in formula 3.

$$n = N_c F_{1/2}\left(\frac{E_{F,n} - E_c}{kT}\right) \quad va \quad p = N_V F_{1/2}\left(\frac{E_V - E_{F,p}}{kT}\right) \tag{3}$$

Here: N_c and N_v are the densities of states in conduction and valence bands, E_c is the minimum energy of conduction band, E_v is the maximum energy of valence band, T is the temperature, k is the Boltzmann constant, $E_{F,n}$ and $E_{F,p}$ are the quasi-fermi energies.

The electron and the hole are separated by the internal electric field of the p-n junction. The electric field generated around ions and charge carriers is calculated using Poisson's equation given in formula 4.

$$\Delta\varphi = -\frac{q}{\varepsilon}\left(p - n - N_D + N_A\right) \tag{4}$$

Here: ε is the permittivity, n and p are the electron and hole concentration, N_D and N_A are the concentrations of donor and acceptor, q is the charge.

Electrons and holes recombine when moving in a semiconductor. There are 3 main types of recombination in semiconductors: Auger, Radiative and Shockley-Read-Hall (SRH). Since silicon is an indirect semiconductor, the percentage of radiative recombination is approximately less than 1 %. Therefore, radiative recombination shouldn't be taken into account when simulation of silicon solar cell. SRH recombination occurs due to defects. Each defect creates a specific energy level in the band gap. An electron in the conduction band falls into the valence band through the energy trap of defects and recombines. The energy generated during recombination turns into phonons and causes heating of the crystal lattice. The amount of SRH recombination is calculated using formula 5 in Sentaurus TCAD.

$$R_{net}^{SRH} = \frac{np - \gamma_n\gamma_p n_{i,eff}^2}{\tau_p\left(n + \gamma_n n_1\right) + \tau_n\left(p + \gamma_p p_1\right)} \tag{5}$$

Here: γ_n, γ_p are the coefficients, τ_n, τ_p are the electron and the hole lifetime, n_1, p_1 are the electron and the hole concentration on the trap.

If the energy generated during the recombination of a carrier is transferred to another carrier, this is called Auger recombination. Therefore, Auger recombination strongly depends on the concentration of charge carriers. Therefore, Auger recombination is dominant in the emitter region of the solar cell. Auger recombination is calculated using formula 6. Auger coefficients depend on the type of material and the doped atom.

$$R_{net}^{A} = \left(C_n n + C_p p\right)\left(np - n_{i,eff}^2\right) \tag{6}$$

Here: C_n, C_p are Auger coefficients, $n_{i,eff}$ is the intrinsic carrier concentration.

Charge carriers have two types of movement: the drift and diffusion. Drift movement occur due to the influence of the electric field and the diffusion movement due to the concentration difference. The movement of charge carriers is represented by drift and diffusion movements. An electric current is created due to the transport of charge carriers. The current is calculated using the continuity equation. Sentaurus TCAD has 3 different continuity equation models: Drift-Diffusion, Thermodynamic and Hydrodynamic. In the thermodynamic and hydrodynamic model, the effect of temperature on the transport of charge carriers is also taken into account. In this article, since we did not study the effect of temperature on the parameters of the solar cell, we calculated the transport of charge carriers using the Drift-Diffusion model given in formula 7.

$$\begin{aligned} \vec{J}_n &= \mu_n(n\nabla E_C - 1.5nkT\nabla\ln m_n) + D_n(\nabla n - n\nabla\ln\gamma_n) \\ \vec{J}_p &= \mu_p(p\nabla E_V + 1.5pkT\nabla\ln m_p) - D_p(\nabla p - p\nabla\ln\gamma_p) \end{aligned} \tag{7}$$

Here: J_n and J_p are the current densities formed by electron and holes, m_n and m_p are the mass of electron and holes, D_n and D_p are the diffusion coefficient of electron and holes, μ_n and μ_p are the mobility of electrons and holes.

3. RESULTS AND DISCUSSION

The AM1.5G spectrum shown in Fig. 2 was used as a light source in the simulation of the solar cell. The intensity of the light was changed from 0.1 sun to 1 suns without changing the spectrum of the light. To model the solar cell under different light intensities, a light spectrum file corresponding to each intensity was created.

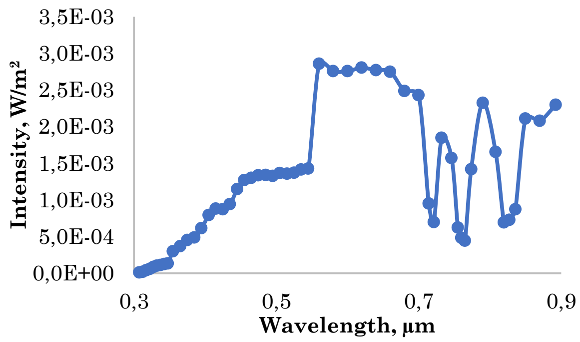

Fig. 2 – AM1.5G spectrum

Fig. 3 shows the dependence of the short-circuit current of a silicon-based solar cell on the light intensity. In the simulation, it was known that the short-circuit current is proportional to the light intensity. The short circuit current at 0.1 sun was 2.55 mA/cm^2 and at 1 sun it was 25.6 mA/cm^2. The short-circuit current variation is equal to 25.6 mA/suns·cm^2. In the Chegaar's experiment [24], it is equal to 32.9 mA/suns·cm^2. In our simulation, the surface of the solar cell only has an anti-reflection layer, so its short-circuit current at 1 suns is 25.6 mA/cm^2. In Chegar's experiment, a silicon-based solar cell with a textured anti-reflection layer was studied. Therefore, difference between the variations of the short-circuit current of the solar cell which measured in experiment and simulated in our model is equal to 7.3 mA/suns·cm^2.

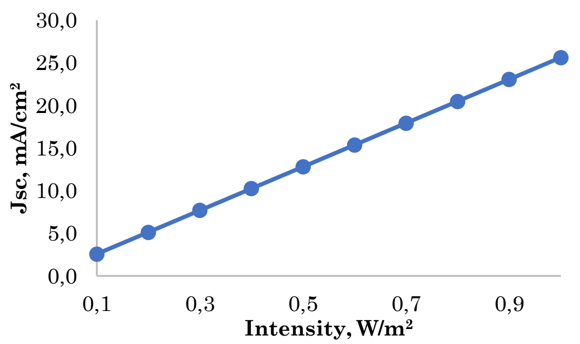

Fig. 3 – Dependence of the short-circuit current of a silicon solar cell on light intensity

Fig. 4 shows the open circuit voltage as a function of light intensity obtained in experiment and simulation. According to the obtained results, it was found that the results of the simulation satisfy the results of the experiment. In both experiment and simulation, it was found that there is logarithmic relationship between the open circuit voltage of a silicon solar cell and light intensity. Therefore, the obtained results satisfy the theoretical expression of the dependence of the open circuit voltage on the light intensity given in formula 8 [25]. This proves that our model is theoretically and practically correct.

$$V_{oc} = V_{oc,1} + \frac{nkT}{q}\ln\left(\frac{E}{E_1}\right) \quad (8)$$

Here: V_{oc} is open circuit voltage, $V_{oc,1}$ is open circuit voltage under one suns illumination, E is intensity of light, E_1 is intensity of one sun.

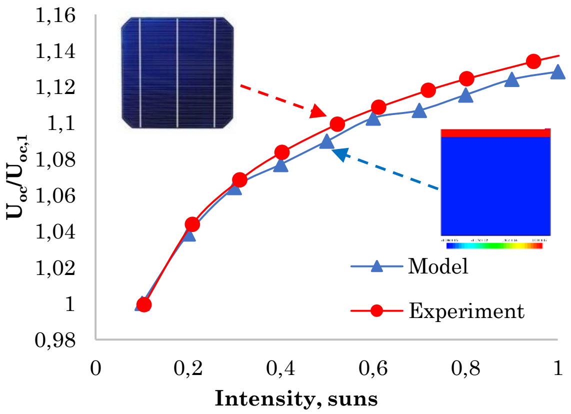

Fig. 4 – The dependence of the open circuit voltage of a silicon solar cell on the light intensity determined in simulation and experiment

The fill factor indicates the resistive properties of the solar cell [26]. Fig. 5 shows the dependence of the fill factor on the light intensity.

In general, the fill factor increased with increasing intensity. Therefore, the resistive properties of the solar cell improve when the light intensity increases. Because, when the light intensity increases, the concentration of charge carriers in silicon increases and therefore the resistivity decreases.

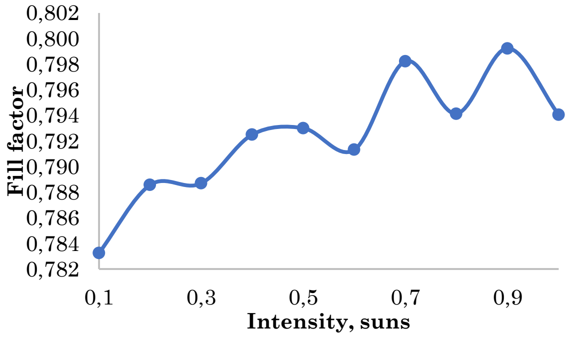

Fig. 5 – Dependence of the fill factor of the silicon-based solar cell on the light intensity

4. CONCLUSION

The concentration of generated charge carriers, the resistivity of the base and the emitter in silicon solar cell changes when the light intensity changes. They cause the changing of photoelectric parameters of the solar cell. Therefore, in this article, the effect of light intensity on the photoelectric parameters of silicon solar cells was determined by simulation and experiment. According to the simulation results, it was found that the short-circuit current is directly proportional to the light intensity. Therefore, a silicon-based *p-n* junction can be used as a pyranometer for measuring light intensity. In addition, the dependence of the open circuit voltage on the light intensity was the same in experiment and modeling. So, the results of the simulation satisfied the experiment. The main task in simulation is to satisfy the results obtained in the model with the experimental results. If the simulation results do not satisfy the experiment, the model is considered incorrect and unsuitable for research. In Sentaurus TCAD, new algorithms should be developed to simulate semiconductor devices. The model of this solar cell in Sentaurus TCAD can also be used in further researches due to agreement of simulation results with experiment. Besides, we can analyze the quality of passivation by using dependence of open circuit voltage on light intensity. So, agreement of simulation results with experiment proved that we can study effect of different materials such as SiO_2 and SiN_x on quality of surface recombination of silicon solar cell in simulation. Passivation of surface affect on kinetic parameters of carriers. that's way, in simulation we can use dependence of open circuit voltage on light intensity to analyze changing of lifetime and diffusion length of carriers.

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Характеристики Suns-V_{oc} кремнієвої сонячної батареї: експериментальне та симуляційне дослідження

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Ефективність сонячних елементів залежить від якості пасивації поверхні. Якість пасивації проаналізовано як функцію залежності напруги холостого ходу від інтенсивності світла. Тому в даній статті досліджено залежність фотоелектричних параметрів сонячної батареї на основі кремнію від інтенсивності світла. Відповідно до отриманих результатів встановлено, що зміна струму короткого замикання через інтенсивність світла дорівнює 25,6 мА/сонц$\cdot$см^2. Узгодженість результатів досліджень і моделювання з результатами експериментів доводить достовірність і правильність моделі. У цій статті експериментально підтверджено модель кремнієвої сонячної батареї Sentaurus TCAD. Таким чином, шляхом моделювання та експерименту досліджено залежність напруги холостого ходу кремнієвої сонячної батареї від інтенсивності світла. Отримана при моделюванні функціональна залежність напруги холостого ходу задовольно узгоджується з експериментом. Створена в Sentaurus TCAD модель сонячної батареї придатна для дослідження. Крім того, коефіцієнт заповнення сонячної батареї зростав зі збільшенням інтенсивності. Це доводить, що резистивні властивості сонячної батареї покращились.

Ключові слова: Сонячна батарея, Симулятор, Напруга холостого ходу, Фотоелектричні параметри, Пасивація.