JOURNAL OF NANO- AND ELECTRONIC PHYSICS
Vol. 14 No 5, 05010(6pp) (2022)
ЖУРНАЛ НАНО- ТА ЕЛЕКТРОННОЇ ФІЗИКИ
Том 14 № 5, 05010(6cc) (2022)

The Effect of Temperature and Base Thickness on Photoelectric Parameters of Amorphous Silicon Solar Cells

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(Received 06 August 2022; revised manuscript received 22 October 2022; published online 28 October 2022)

One of the important tasks of photovoltaics is the design of flexible solar cells that are resistant to environmental influences and designed to cover surfaces of various shapes. Therefore, pin-structured amorphous silicon-based solar cells with flexible properties were studied in this study. Amorphous silicon has a higher absorption coefficient and band gap than crystalline silicon. A high absorption coefficient proves that a high efficiency can be achieved in thin films. According to the obtained simulation results, the maximum values of the open circuit voltage, short-circuit current, fill factor and efficiency of the amorphous silicon-based solar cell were 1.2044 V, 13.49 mA/cm^2, 80.03 % and 12.18 %, respectively, as well as achieved them at a base thickness of 35, 20, 3 and 15 μm, respectively. The effect of temperature on an amorphous silicon-based solar cell with optimal thickness was studied because amorphous silicon is very sensitive to external influences such as light intensity and temperature. Therefore, it is important to study the effect of temperature on the properties of amorphous silicon-based solar cells. As the temperature increased, the open circuit voltage decreased, but the short-circuit current, fill factor, and efficiency increased. It was found that the temperature coefficients of open circuit voltage, short circuit current, fill factor and efficiency are -1.68×10^{-3}, 2.24×10^{-3}, 4.5×10^{-5} and 2.27×10^{-4} 1/K, respectively.

Keywords: Amorphous silicon, Simulation, Solar cell, Numerical method, Thickness, Temperature.

DOI: 10.21272/jnep.14(5).05010 PACS numbers: 85.60.Bt, 78.20.Bh, 84.60.Jt

1. INTRODUCTION

Interest in renewable energy sources is increasing day by day because the reserves of non-renewable energy sources are decreasing sharply. Renewable energy sources are the best way to meet future energy needs. Renewable energy sources include solar, wind and water [1]. Energy from the sun is converted into heat and electricity. Heat energy from the sun is used to heat water in solar collectors. A device that converts solar energy into electricity is called a solar cell.

Solar cells are mainly made of different semiconductors [2]. Depending on the *p-n* junction, they are divided into homo- and hetero-junction types [3], single and multi-junction types depending on the number of *p-n* junctions [4]. There are three generations of solar cells. However, 90 % of solar cells produced in the industry today are crystalline silicon-based solar cells even though they are 1st generation solar cells [5]. The maximum efficiency of industrially produced solar cells is 24 %. According to the Shockley-Queisser theory, the efficiency of silicon-based solar cells does not exceed 29 % [6]. The need for electricity cannot be met with the help of a silicon-based solar cell because its cost is expensive, and the efficiency is low. Therefore, scientists use various materials to develop a low-cost and high-efficiency solar cell. Currently, interest in polymer [7], organic [8] and perovskite materials has increased dramatically due to their low cost. However, the development of new structures without abandoning silicon has accelerated. A HIT structure [9] was developed by forming a heterojunction using amorphous silicon and crystalline silicon, and for the first time, the efficiency approached to 28 %. HIT structured solar cells were invented by the PANASONIC company and are currently manufactured commercially.

There are three main losses [10] in solar cells: optical, thermal and electrical. Optical losses include reflection of light from the surface, non-absorption and spectral mismatch [11]. To reduce optical losses, the surface of the solar cell is covered with various antireflective layers [12], textures [13], and various nanoparticles [14] are introduced. Thermal losses include self-heating of the solar cell. The solar cell is heated due to absorption of infrared light in the back contact or thermalization of high-energy electrons. In order to reduce the amount of infrared light absorbed in the back contact, it is proposed to make it in the form of a grid [15]. To reduce the number of high-energy electrons and spectral mismatch, the surface of the solar cell is coated with various luminescent materials [16].

Solar cells made of crystalline semiconductor break easily under the influence of mechanical stress. It is impossible to cover cars, airplanes, roofs of various shapes with crystalline silicon-based solar cells. Therefore, flexible solar cells retain their interest despite their low efficiency. Flexible solar cells are mainly made of amorphous silicon with a pin structure. Amorphous silicon can achieve good efficiency in thin layers due to its high absorption coefficient. An amorphous silicon-based solar cell degrades after a certain period of time when illuminated. This phenomenon is called the Staebler-Wronski effect. Hydrogen in amorphous silicon is very sensitive to external influences because it is weakly bonded to silicon. Therefore, in this article, the effect of temperature and layer thickness on amorphous silicon-based solar cell was studied.

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2. MATERIALS AND METHOD

2.1 Simulation

One software for simulating solar cells is SCAPS-1D, developed by Bulgerman, a researcher at the University of Ghent in Belgium. This program is designed to make calculations of 1D solar cells [17]. It mainly contains the physical properties of semiconductor substances. Because when this program was first presented to the public, it was intended to model solar cells based only on semiconductors. Later, in the process of simulation by the user, the physical properties of the optional material were given, and an opportunity was created to create this material. And this greatly helped the popularity of this program. The SCAPS-1D program does not include a material file for amorphous silicon either. In order to model an amorphous silicon-based solar cell, experimentally determined and reliable physical properties of amorphous silicon must be collected. Table 1 lists the physical properties of intrinsic, *n*-type and *p*-type amorphous silicon collected from reliable experimental results [18]. Also, a pin amorphous silicon based solar cell was modeled using these properties.

Table 1 – Material properties required for modeling the *p-i-n* amorphous silicon-based solar cell

Parameters	*p*-layer	*i*-layer	*n*-layer
Permittivity	7.2	11.9	11.9
Electron affinity (eV)	3.9	4	3.99
Band gap (eV)	1.95	1.78	1.8
Electron mobility (10^{-4} m²/Vs)	20	20	20
Hole mobility (10^{-4} m²/Vs)	5	5	5
Density of states in the conduction band (m^{-3})	1×10^{26}	1×10^{26}	1×10^{26}
Density of states in the valence band (m^{-3})	1×10^{26}	1×10^{26}	1×10^{26}

After the characteristics of the materials are given and the layers are formed, the direction of light falling on the general structure is determined. Through this, it is possible to determine the light sensitivity of both sides of the solar cell by illuminating from the back and front without changing the structure, and it is possible to model a solar cell with a straight and inverted structure through a single model.

2.2 Theory

Among the processes that take place inside a semiconductor device, the most common is the state of equilibrium. In this case, to model the semiconductor device, at least the Poisson equation given in formula (1) should be solved:

$$\Delta\varphi = -\frac{q}{\varepsilon}\left(p - n + N_D + N_A\right). \tag{1}$$

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

The electron and hole concentrations n and p are calculated by the Fermi distribution given by formulas (2) and (3) [19]:

$$n = N_c F_{1/2}\left(\frac{E_{F,n} - E_c}{kT}\right), \tag{2}$$

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

Here, $F_{1/2}$ is the Fermi integral, E_c is the conduction band energy, E_v is the valence band energy, $E_{F,n}$ is the quasi Fermi energy for electrons, $E_{F,p}$ is the quasi Fermi energy for holes, T is the temperature, N_c is the density of states in the conduction band, N_v is the density of states in the valence band, and k is the Boltzmann constant.

If a semiconductor device is energized, illuminated, or heated, transport of charge carriers occurs. That is, the state of equilibrium is disturbed. So, due to the illumination of solar cells, it is necessary to take into account the transport of charge carriers in simulation. The transport of charge carriers creates a current. The connection between the concentration of charge carriers and the current density is generally expressed by the continuity equation given in formula (4) and formula (5) [20]:

$$\nabla \cdot \vec{J}_n = qR_{net,n} + q\frac{\partial n}{\partial t}, \tag{4}$$

$$-\nabla \vec{J}_p = qR_{net,p} + q\frac{\partial p}{\partial t}. \tag{5}$$

Here, J_n and J_p are the current densities of electrons and holes, $R_{net,p}$ and $R_{net,n}$ are the net recombinations of electrons and holes, t is the time.

Based on the above equations, SCAPS-1D, like other programs, calculates the electrical characteristics of devices. Also, since it is a 1D dimensional modeling program, it mainly uses the Transfer Matrix Method (TMM) [21] to determine the optical properties. However, absorption, transmission and reflection coefficients are not output as a result, instead the generation rate in the layers is calculated using the Burger-Lambert law [22].

3. RESULTS AND DISCUSSION

3.1 Main Characteristics of Amorphous Silicon Solar Cells

To determine the quality of a solar cell, it is enough to measure *I-V* and spectral characteristics because the *I-V* characteristic indicates the quality of the *p-n* junction and contacts of the solar cell, and the spectral characteristic indicates its optical properties. Fig. 1 shows the *I-V* characteristic of a *p-i-n* amorphous silicon solar cell. In the model, a structure was made with the following dimensions and input concentrations: d_n = 200 nm, d_p = 200 nm, d_i = 5 μm, N_A = 1e16 cm^{-3} and N_D = 1e17 cm^{-3}. It was found by analyzing *I-V* characteristics of the amorphous silicon solar cell that the short-circuit current was 12 mA/cm² and the open circuit was 1.2 V.

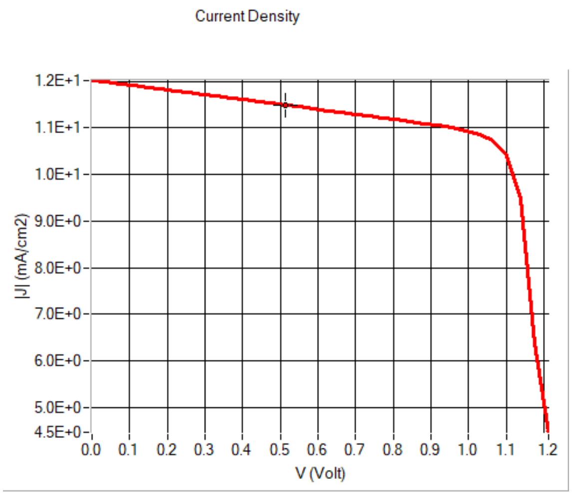

Fig. 1 – *I-V* characteristic of a *p-i-n* amorphous silicon solar cell: d_n = 200 nm, d_p = 200 nm, d_i = 5 μm, N_A = 1e16 cm^{-3}, and N_D = 1e17 cm^{-3}

As mentioned above, to determine the optical properties, it is enough to measure the spectral characteristics. Therefore, Fig. 2 shows the dependence of the quantum efficiency of a *p-i-n* amorphous silicon-based solar cell on the wavelength of light. Similarly, SCAPS-1D used the AM1.5G spectrum to illuminate the solar cell.

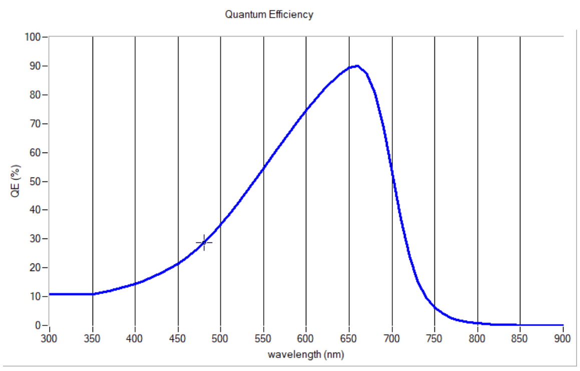

Fig. 2 – Quantum efficiency of a *p-i-n* amorphous silicon-based solar cell. Here, d_n = 200 nm, d_p = 200 nm, d_i = 5 μm, N_A = 1e16 cm^{-3} and N_D = 1e17 cm^{-3}

3.2 Influence of the Base Thickness on Photoelectric Parameters

When we studied the optical properties of amorphous silicon-based solar cells, we also studied their thickness dependence. This section discusses the dependence of electrical properties on the base thickness. The basic photoelectric parameters of a solar cell are the open-circuit voltage, fill factor, short-circuit current and efficiency. All of them are determined by analyzing the *I-V* characteristic. Besides, all parameters change differently when the thickness increases. Fig. 3 shows the dependence of the open-circuit voltage of the *p-i-n* amorphous silicon-based solar cell on the base thickness. The operating circuit voltage increased dramatically when the thickness increased from 5 to 15 μm. When the thickness increased from 15 to 35 μm, the open-circuit voltage increased very little, and at thicknesses greater than 35 μm, the open-circuit voltage decreased. So, the open-circuit voltage reaches its maximum value when the base thickness is 35 μm. When the base thickness increases, the amount of charge carriers increases, but, at the same time, it becomes difficult to deliver them to contacts through an internal electric field due to increasing recombination rate [23].

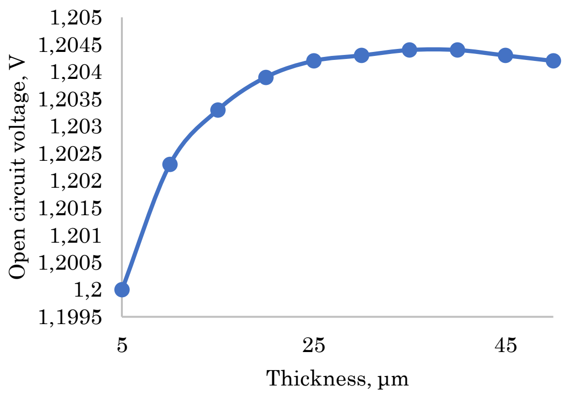

Fig. 3 – Dependence of the open-circuit voltage of a *p-i-n* amorphous silicon solar cell on the base thickness

The short-circuit current is very strongly connected to the base thickness because the volume of generation of excitons also increases when the thickness increases. This leads to an increase in carriers. Fig. 4 shows the dependence of the short-circuit current of a *p-i-n* amorphous silicon-based solar cell on the base thickness. When the thickness increased from 5 to 20 μm, the short-circuit current increased sharply to 1.49 mA/cm^2. When the thickness increased from 20 to 50 μm, the short-circuit current decreased sharply and almost linearly to 2.19 mA/cm^2. The increase and decrease of the short-circuit current of the solar cell according to the thickness are mainly explained by the relationship between recombination and generation. As the thickness increases, the amount of recombination also increases. Above, when the variation of photogeneration with thickness was determined, it increased slightly with increasing thickness because when the thickness increases, the probability of exciton generation also increases, but the probability of separating them using an electric field and delivering them to the contacts decreases. Therefore, when the thickness of amorphous silicon-based solar cells increases, the short-circuit current decreases. This means that recombination increases faster than generation in this interval. The best short-circuit current was observed at a thickness of 20 μm, and it was equal to 13.49 mA/cm^2.

The fill factor is used to determine the quality of the *p-n* junction and contacts in the solar cell. Since the maximum value of the fill factor is between 0-5 μm thickness, we again modeled the solar elements by increasing the thickness with a step of 0.5 μm in this range and got the results. Fig. 5 shows the dependence of the fill factor of the *p-i-n* amorphous silicon-based solar cell on the base thickness. When the thickness increased from 0.5 to 3 μm, the value of the fill factor increased by 4.36 %. When the thickness increased from 3 to 50 μm, the fill factor decreased by 10.58 %. So, the maximum value of the fill factor of 80.03 % was observed at a thickness of 3 μm. The reason for this is that the quality of the *p-i-n* junction improves at this thickness, and most of the generated excitons are able to separate and reach the contact due to the internal electric field. Also, the thickness of the base directly affects the series and shunt resistances of the solar cell, and the fill factor is strongly dependent on them. That is why the fill factor is observed to increase and decrease with increasing layer thickness. An increase or decrease of the parameters in some interval indicates the interaction of several processes.

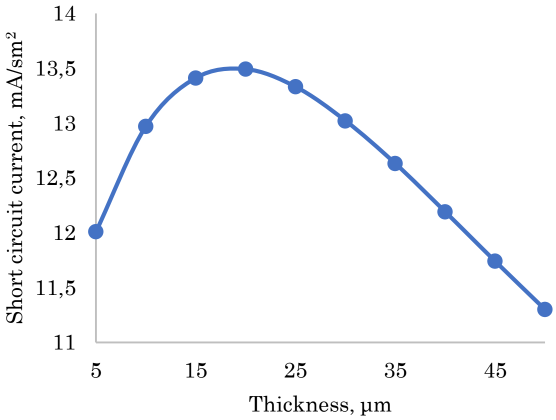

Fig. 4 – Dependence of the short circuit current of *p-i-n* amorphous silicon solar cell on the base thickness

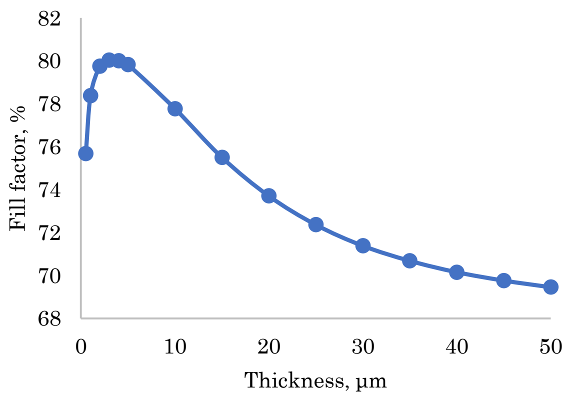

Fig. 5 – Dependence of the fill factor of *p-i-n* amorphous silicon solar cell on the base thickness

The most important parameter of solar cells is their efficiency. The efficiency is the ratio of the maximum power generated by the solar cell to the light power falling on its surface. Fig. 6 shows the dependence of the fill factor of the *p-i-n* amorphous silicon-based solar cell on the base thickness. When the thickness increases from 0.5 to 15 µm, the efficiency coefficient increases by 4.41 %, and when it increases from 15 to 50 µm, the efficiency decreases by 2.73 %.

From the obtained results, we can conclude that it is preferable to make the thickness of the amorphous silicon-based solar cell thinner. It was known that each photoelectric parameter reaches its maximum value at different values of the thickness. Therefore, the open circuit voltage, the short circuit current, fill factor and efficiency reach their maximum values at a thickness of 35, 20, 3 and 15 µm, respectively.

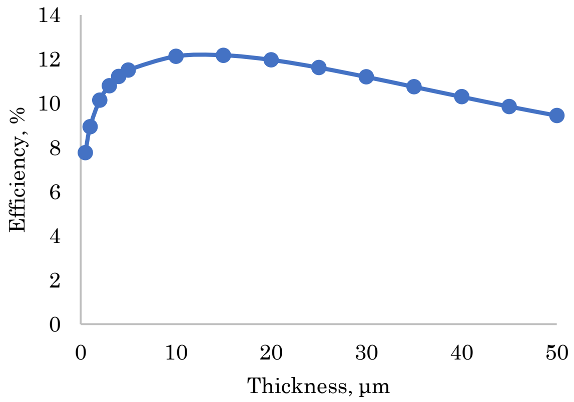

Fig. 6 – Dependence of the efficiency of *p-i-n* amorphous silicon solar cell on the base thickness

3.3 Influence of Temperature on Photoelectric Parameters

It is important to take into account the influence of the environment on solar cells. Solar cells are devices that are very sensitive to changes in light intensity and temperature [24]. In this section, the effect of temperature on the photoelectric parameters of amorphous silicon-based solar cells was simulated using the SCAPS-1D program. The effect of temperature on the performance of a pin solar cell based on amorphous silicon with a base thickness of 15 µm was studied. The temperature of the solar cell was changed from 250 to 350 K in steps of 10 K, that is, one structure was modeled 10 times at different temperatures. Table 2 presents the photoelectric parameters of a pin amorphous silicon-based solar cell with a base thickness of 15 µm at different temperatures. The reason for choosing this temperature range is that solar cells are mainly used in space and on the surface in this temperature range.

Table 2 – Photoelectric parameters of a pin amorphous silicon-based solar cell with a base thickness of 15 µm at different temperatures

Temperature, K	U_{oc}, **V**	I_{sc}, **mA/sm²**	**FF, %**	η, **%**
250	1.3179	12.43	75.28	12.34
260	1.2949	12.57	75.31	12.26
270	1.2720	12.73	75.35	12.20
280	1.2493	12.92	75.38	12.17
290	1.2267	13.15	75.42	12.16
300	1.2044	13.41	75.45	12.18
310	1.1823	13.70	75.48	12.23
320	1.1605	14.03	75.51	12.30
330	1.1389	14.40	75.55	12.39
340	1.1175	14.80	75.59	12.50
350	1.0965	15.22	75.62	12.62

According to the obtained simulation results, when the temperature changes from 250 to 350 K, the open-circuit voltage decreases by 0.2214 V, the short-circuit current increases by 2.79 mA/cm², the fill factor increases by 0.34 %, and the efficiency increases by 0.28 %. The efficiency of crystalline silicon-based solar cells decreases [25] with increasing temperature, but the efficiency of amorphous silicon-based solar cells increases. This shows another advantage of the amorphous silicon-based solar cell. It was found that the temperature coefficient of the open-circuit voltage of an amorphous silicon-based solar cell is -1.68×10^{-3} 1/K, the temperature coefficient of the short-circuit current is 2.24×10^{-3} 1/K, the temperature coefficient of the fill factor is 4.5×10^{-5} 1/K, and the temperature coefficient of efficiency is 2.27×10^{-4} 1/K. The efficiency of the amorphous silicon-based solar cell increased when the temperature increased due to the fact that the temperature coefficient of the short-circuit current was greater than the temperature coefficient of the open-circuit voltage.

4. CONCLUSIONS

In this scientific work, the effect of temperature and base thickness on the photoelectric parameters of the amorphous silicon-based solar cell was determined using SCAPS-1D. According to the obtained results, when the temperature increases, the short-circuit current of the amorphous silicon-based solar cell increases and the open-circuit voltage decreases. However, in general, unlike crystalline silicon-based solar cells, the efficiency increased with increasing temperature because the rate of increase in the short-circuit current is greater than the rate of decrease in the open-circuit voltage. In conclusion, the amorphous silicon-based solar cell can be used in areas with high temperatures. Each photoelectric parameter reaches maximum values at different thicknesses. This amorphous silicon-based pin structure can be used in various optoelectronic devices depending on the optimal value of the photoelectric parameters. For example, for a solar cell, a structure with a base thickness that achieves the maximum efficiency and a structure with a base thickness that achieves the maximum short-circuit current for a pyranometer are important. Based on the results obtained in this scientific work, in the future, we plan to cover amorphous silicon-based solar cells with optimal thickness with various optical layers to make them suitable for concentrating photovoltaic devices and to further increase the efficiency.

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Вплив температури та товщини основи на фотоелектричні параметри сонячних елементів з аморфного кремнію

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Одним із важливих завдань фотовольтаїки є конструювання гнучких сонячних елементів, стійких до впливу навколишнього середовища та призначених для покриття поверхонь різної форми. Таким чином, у дослідженні були вивчені сонячні елементи на основі аморфного кремнію. Аморфний кремній має більший коефіцієнт поглинання та ширину забороненої зони, ніж кристалічний кремній. Високий коефіцієнт поглинання доводить, що в тонких плівках можна досягти високого ККД. Згідно з отриманими результатами моделювання, максимальні значення напруги холостого ходу, струму короткого замикання, коефіцієнта заповнення та ККД сонячного елемента на основі аморфного кремнію становили 1,2044 В; 13,49 мА/см²; 80,03 % та 12,18 % відповідно, і були досягнуті при товщинах основи 35, 20, 3 і 15 мкм відповідно. Було вивчено вплив температури на сонячний елемент на основі аморфного кремнію оптимальної товщини, оскільки аморфний кремній дуже чутливий до зовнішніх впливів, таких як інтенсивність світла та температура. Тому важливо вивчити вплив температури на властивості сонячних елементів на основі аморфного кремнію. З підвищенням температури напруга холостого ходу зменшувалася, але струм короткого замикання, коефіцієнт заповнення та ККД збільшувалися. Температурні коефіцієнти напруги холостого ходу, струму короткого замикання, коефіцієнта заповнення та ККД становлять відповідно $-1,68\times10^{-3}$; $2,24\times10^{-3}$; $4,5\times10^{-5}$ та $2,27\times10^{-4}$ 1/K.

Ключові слова: Аморфний кремній, Моделювання, Сонячний елемент, Чисельний метод, Товщина, Температура.