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Study of the Temperature Coefficient of the Main Photoelectric Parameters of Silicon Solar Cells with Various Nanoparticles

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It is significant to improve the photoelectric parameters of thin-film silicon-based solar cells. There are some methods to enhance the optical and electrical properties of thin-film silicon-based solar cells. One of them is to insert various metal nanoparticles into a thin-film solar cell. Nanoparticles have an effect on the photoelectric parameters, also on their temperature coefficients. In this work, the effect of Au, Ag, Pt, Ti, Co, Al, Cu nanoparticles on the temperature coefficient of the photoelectric parameters of a thin film silicon-based solar cell was studied. The calculations were performed for temperatures ranging from 250 to 350 K. In this research, it was found that the open-circuit voltage of a solar cell with Pt and Ti nanoparticles changes by 0.4 % when the temperature changes by 1 K. Besides, it was revealed that the short-circuit current of a solar cell with Ag nanoparticles has the greatest effect on the temperature coefficient, that is 6.3 times.

Keywords: Modeling, Nanoparticle, Solar cell, Silicon, Temperature coefficient.

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1. INTRODUCTION

The best way is to meet society's demand for electricity with renewable energy sources because they do not harm the environment. There are many types of renewable energy sources. Solar energy is one of them. Electricity and heat can be given from solar energy. A device that converts solar energy into electricity is a solar cell.

Scientists are doing a lot of research to increase the efficiency of solar cells and reduce their cost. Thin silicon-based solar cells were designed to reduce costs. Since the optical absorption coefficient of a solar cell directly depends on its thickness, the absorption coefficient decreases sharply as the thickness decreases. To overcome this problem, nanostructures were formed on the surface of a solar cell. The absorption coefficient of silicon-based nano- and microscale solar cells increased by the formation of nanocones and nanoholes on their surface [1]. The efficiency of amorphous silicon based tandem solar cells with a thickness of 200 to 500 nm can be increased by 15 % by nanotexturing with ZnO on their surface, and this result was found by using the Monte-Carlo simulation method [2]. According to Shockley-Queisser's theoretical calculations, the maximum efficiency of simple silicon-based solar cells does not exceed 29 %. However, it was found that the Shockley-Queisser limit was increased to 42 % for a single-junction solar cell based on nanostructured silicon [3].

It is important to study the effect of temperature on the photoelectric parameters of solar cells, as they are used in different regions and in different climatic conditions. Experiments have shown that when the temperature increases from 79 to 300 K, the operating voltage of a simple silicon-based solar cell decreases by 36 % and the short-circuit current increases by 188 % [4]. But the decrease in the output power of a nanoscale silicon-based solar cell to 79.17 % in the temperature range from 280 to 340 K was calculated using Silvaco TCAD [5]. The efficiency of a nanostructured and nanoporous silicon-based solar cell decreased by 52.5 % when the temperature changed from 300 to 400 K, which was calculated using time-dependent functions and numerical methods [6].

The absorption coefficient of thin-film solar cells can be improved by introducing metal nanoparticles. An improvement of the absorption coefficient and generation of hot electrons when silver or gold nanoparticles are inserted into the optical layer, and therefore, an increase in the photocurrent, were found experimentally [7].

The effect of each nanoparticle on the properties of a solar cell is different. Another important task is to study the effect of nanoparticles on the photoelectric parameters of solar cells, including temperature coefficients. This is because it is possible to select the type of nanoparticle to be inserted depending on where a solar cell is used. It also determines the optimal nanoparticle for a silicon-based solar cell.

2. METHOD

In this paper, models of solar cells with various metal nanoparticles have been developed using the Sentaurus TCAD software package. The Sentaurus TCAD software package consists of 23 instruments, of which 17 are basic and 4 are additional. There are four main tools used to model solar cells: Sentaurus Structure Editor, Sentaurus Device, Sentaurus Visual, and Sentaurus Workbench. Each instrument has its own task. The Sentaurus Structure Editor is a tool for developing 3D/2D geometric models of semiconductor devices. The Sentaurus Structure Editor has only an SDE module. In SDE, geometric models can be created in two different styles. First, it is possible to create geometric models using standard shapes in the SDE edit window. But it is more difficult to create complex geometric models by using this style. Second, geometric

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models can be created by writing codes. The Sentaurus Device (SDevice) is used to simulate semiconductor devices and calculate their electrical, optical, mechanical, thermal, and other properties. In the Sentaurus Visual Instrument, diagrams and visual graphs are generated based on the results calculated in SDevice. The Sentarus Workbench (SWB) is an environment that allows the above three tools to work together. It greatly expands the possibilities of Sentaurus.

2.1 Geometric Model

The geometric model of a nanoparticles induced solar cell (NISC) was generated by coding. A perfect algorithm was also developed by a loop operator to create metal nanoparticles in a solar cell. This unique algorithm was also used to input all types of nanoparticles into different areas of the solar cell (Appendix 1).

As shown in Fig. 1, a metal nanoparticle was injected into the n-region of a solar cell. The radius of the metal nanoparticle is $r = 20$ nm. The size of the solar cell is proportional to the nanoparticle radius (Table 1).

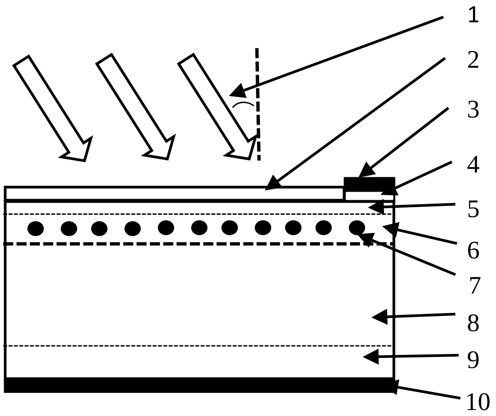

Fig. 1 – Schematic diagram of a silicon solar cell with metal nanoparticles: 1 – light ray, 2 – antireflective coating, 3 – front contact, 4 – front contact region, 5 – high doping n^{++}-region, 6 – n-region, 7 – metal nanoparticle, 8 – p-region, 9 – high doping p^{++}-region, 10 – rear contact

Table 1 – All information about the solar cell with metal nanoparticles

	Width, μm	Thickness	Doping type	Doping concentration	Material type
Front contact region	0.2	$3r$	P	1e19	Silicon
Optical coating	1.8	$3r$	–	–	SiO_2
n^{++}-region	2	$5r$	P	1e18	Silicon
n-region	2	$7r$	P	1e17	Silicon
p-region	2	$46r$	B	1e15	Silicon
p^{++}-region	2	$4r$	B	1e16	Silicon

2.2 Theory

In this paper, the Sentaurus Device was used to calculate the photoelectric parameters of NICS at different temperatures. In the Sentaurus Device, numerical methods are used to calculate parameters. Numerical methods are built on the basis of differential equations, experimental results, physical laws, and statistical distributions. Basically, the results obtained in the experiment and empirical formulas are taken as the initial conditions of the differential equations.

To determine the optical properties of a solar cell, the wavelength dependence of the complex refractive index determined experimentally, the Spectral mismatch and the Transfer Matrix Method are used. This model also takes into account the temperature dependence of the complex refractive index:

$$\Delta n = n_0 \cdot C_{n,T} \cdot \left(T - T_{par}\right), \qquad (1)$$

where Δn is the change in the refractive index due to temperature, n_0 is the refractive index at a temperature T_{par}, T is the temperature, $C_{n,T}$, T_{par} are constants.

To determine the electrical properties of a solar cell, at least the electrostatic potential (formula (2)) must be calculated using the Poisson equation. So, the distribution of charge carriers is determined by Fermi-Dirac statistics. If a semiconductor device is in equilibrium, the potential difference between the contacts is zero, and it is sufficient to determine its electrical properties by calculating the Fermi-Dirac distribution and the electrostatic potential

$$\Delta\varphi = -\frac{q}{\varepsilon}\left(p - n + N_D + N_A\right), \qquad (2)$$

where ε is the permittivity, n and p are the concentrations of electrons and holes, respectively, N_D and N_A are the concentrations of donors and acceptors, respectively, q is the electron charge.

The potential difference occurs when a solar cell is illuminated. This means that there is a charge transfer in the solar cell. The charge transfer is calculated by solving the continuity equation. There are different forms of the continuity equation. In this paper, a thermodynamic form of the continuity equation was used to calculate the charge transfer. This is because the effect of temperature on the charge carrier transfer is also taken into account. Based on the thermodynamic model, the current densities for electrons and holes by using formulas (3) and (4) were calculated.

$$J_n = -nq\mu_n\left(\nabla F_n + P_n \nabla T\right), \qquad (3)$$

$$J_p = -pq\mu_p\left(\nabla F_p + P_p \nabla T\right), \qquad (4)$$

where J_n, J_p are the current densities of electrons and holes, respectively; n, p are the concentrations of electrons and holes, respectively; μ_n, μ_p are the mobilities of electrons and holes, respectively; P_n, P_p are the heat powers, F_n, F_p are the Fermi potentials.

The amount of heat generated in different parts of the NISC was calculated based on a thermodynamic model.

$$\frac{\partial}{\partial t}\left(c_L T\right)-\nabla\left(k\nabla T\right)=-\nabla\left[\left(P_n T+F_n\right)\vec{J}_n+\left(P_p T+F_p\right)\vec{J}_p\right]-\frac{1}{q}\left(E_c+\frac{3}{2}kT\right)\left(\nabla\vec{J}_n-qR_{net,n}\right)-\frac{1}{q}\left(E_v+\frac{3}{2}kT\right)\left(-\nabla\vec{J}_p-qR_{net,n}\right)+\hbar\omega G^{opt} \quad (5)$$

$$\frac{\partial}{\partial t}\left(c_L T\right)-\nabla\left(k\nabla T\right)=-\nabla\left[\left(PT+F_m\right)\vec{J}_m\right], \quad (6)$$

where k is the heat conductance, c_L is the heat capacity, E_c is the minimum energy of the conduction band, E_v is the maximum energy of the valence band, G_{opt} is the optical generation, $R_{net,n}$ and $R_{net,p}$ are the net recombinations, J_n and J_p are the current densities calculated by formulas (3) and (4), t is the time, F_m is the metal Fermi state, J_m is the current density in metal.

Formula (5) is a time-dependent equation for the heat energy of a semiconductor crystal. Let us calculate the amount of heat in a metal nanoparticle by using formula (6). If temperature is taken as a time-independent parameter $\frac{\partial}{\partial t}\left(c_L T\right)=0$, then formulas (5) and (6) change to the equation for a stationary form.

3. RESULTS AND DISCUSSION

In this article, all the parameters obtained are given in relation to the parameters of a simple solar cell (SSC). This is because the effect of a metal nanoparticle on the temperature coefficient of the solar cell parameters can be determined by the following conditions: $P_n/P_s > 1$ (the nanoparticle increases the P parameter), $P_n/P_s < 1$ (the nanoparticle decreases the P parameter), $P_n/P_s = 1$ (the nanoparticle does not affect the P parameter). If there is a function $f(T)$ between P_n/P_s and T, then for $d(f(T))/dT > 0$ the function increases as the nanoparticle improves the temperature coefficient of the parameter. For $d(f(T))/dT < 0$, the nanoparticle worsens the temperature coefficient of the parameter if the function decreases, and for $d(f(T))/dT = 0$ the nanoparticle does not affect the temperature coefficient of the parameter if the function does not change. Based on the above conditions, the following results are analyzed.

Fig. 2 shows that the open-circuit voltage of an SSC increases by 42 % when the temperature increases from 250 to 350 K. Experimental studies by Radziemskaya and Klugman found that the open-circuit voltage changes by 0.4 % when the temperature changes by 1 K [8]. In fact, Green developed formula (7) to determine the temperature coefficient of the open-circuit voltage [9]. The nanoparticle size was 20 nm. For this case, the temperature dependence of the open-circuit voltage of NISCs, which include copper, gold, silver, aluminum, cobalt, platinum, and titanium metal nanoparticles, is shown in Fig. 3. The temperature dependence of the open-circuit voltage of NISCs with platinum and titanium metal nanoparticles was found to be better than that of an SSC. It was found that the open-circuit voltage of NISCs with silver and cobalt nanoparticles does not depend very well on temperature, since the open-circuit voltage in them decreases more rapidly than that in an SSC with increasing temperature. The temperature dependence of the open-circuit voltage of NISCs, which include gold, aluminum and copper nanoparticles, is almost indistinguishable from that of an SSC. Pervin found that the open-circuit voltage of a NISC with indium nanoparticles changes by 0.2 % when the temperature changes by 1 K [10]. The open-circuit voltage of silicon-based NISCs with platinum and titanium nanoparticles changes by 0.4 % when the temperature changes by 1 K. This means that platinum and titanium nanoparticles improve the temperature coefficient of a thin-film silicon-based solar cell. This is because the nanoparticles change the width of the band gap of silicon by emitting additional hot electrons due to the plasmonic effect. Therefore, the open-circuit voltage depends on the width of the band gap

$$\frac{dU_{oc}}{dT}=-\frac{\frac{nE_g}{mq}-U_{oc}+\frac{\gamma nkT}{q}}{T} \quad (7)$$

where E_g is the band gap energy, γ, m are constants, U_{oc} is the open-circuit voltage, k is the Boltzmann constant, n is the ideality factor.

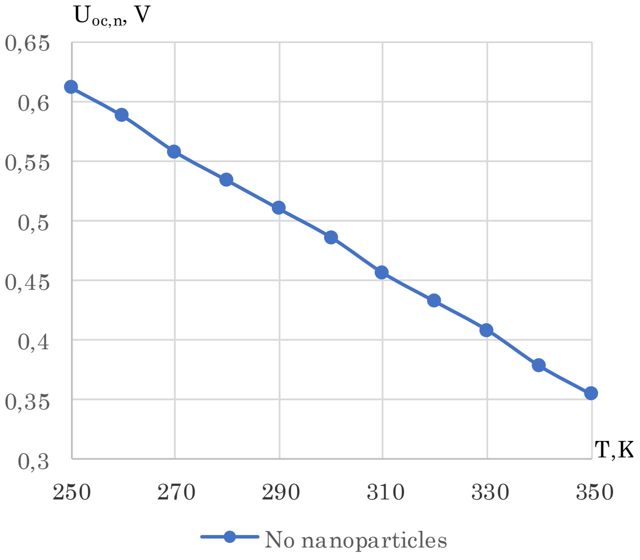

Fig. 2 – Temperature dependence of the open circuit voltage of an SSC

Fig. 4 shows the temperature dependence of the fill factor of an SSC. This means that the fill factor of an SSC changes by 0.16 % when the temperature changes by 1 K. In experiments conducted by Cuce, it was found that the fill factor of a single-crystalline silicon-based solar cell changes by 0.18 % when the temperature changes by 1 K [11]. This result proves that the nano-sized silicon-based solar cell has better temperature stability of the fill factor than an SSC. Fig. 5 shows the temperature dependence of the ratio of the fill factors of NISCs to the fill factor of an SSC. It was found that the temperature dependence of the fill factors of all NISCs, except for a NISC with injected cobalt nanoparticles, is better than that of an SSC.

Table 2 shows the temperature coefficients of the main photoelectric parameters of NISCs with different nanoparticles. Therefore, nanoparticles mainly affect the current and power produced by a solar cell.

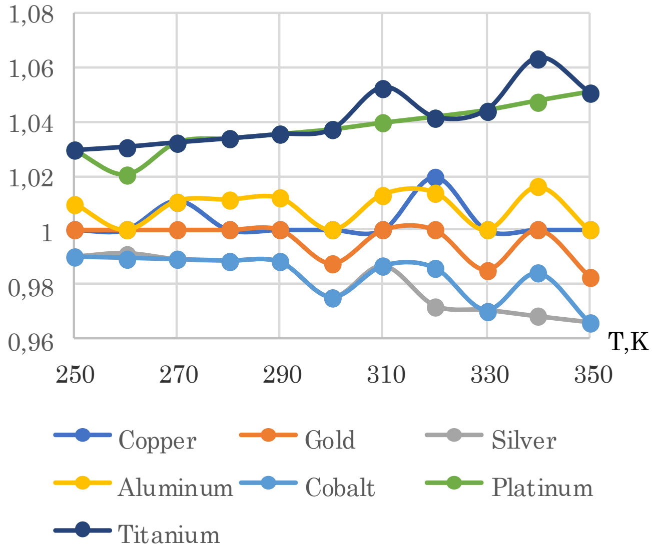

Fig. 3 – Temperature dependence of the ratio of the open circuit voltage of NISCs to the open circuit voltage of an SSC

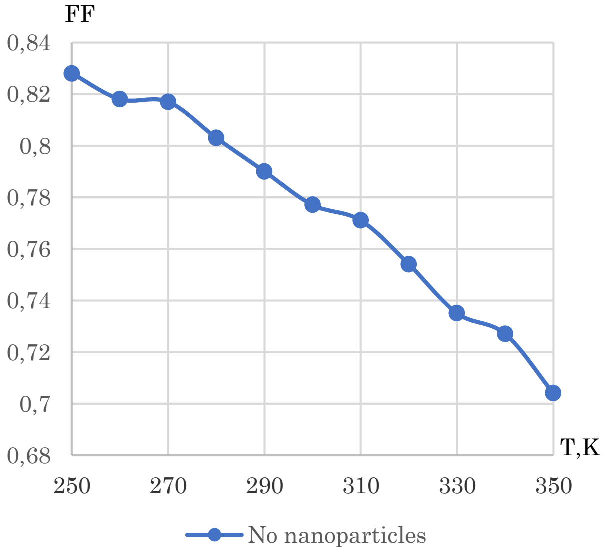

Fig. 4 – Temperature dependence of the fill factor of an SSC

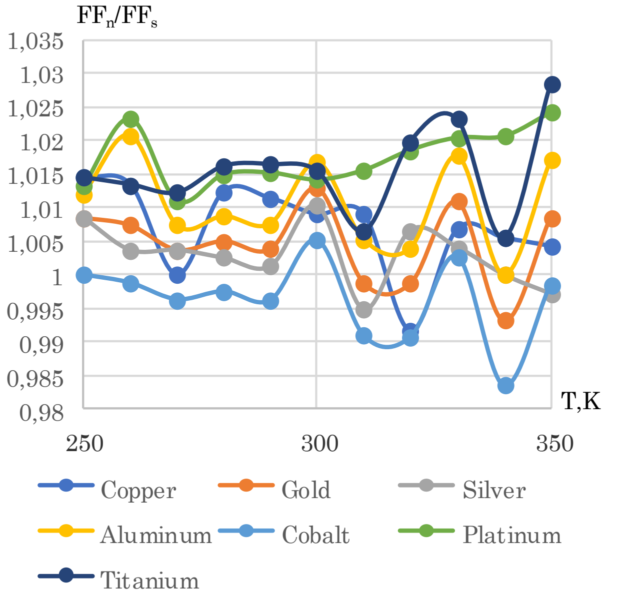

Fig. 5 – Temperature dependence of the ratio of the fill factor of NISCs to the fill factor of an SSC

The temperature coefficient of the short-circuit current is 4 times higher for NISCs than that for an SSC. So, more free electrons are generated from the metal nanoparticles as heat increases. The temperature coefficients of photoelectric parameters for nanosized pin coaxial silicon-based solar cell $\frac{1}{U_{oc}}\frac{\partial U_{oc}}{\partial T} = 6.67 \cdot 10^{-3} \text{K}^{-1}$, $\frac{1}{I_{sc}}\frac{\partial I_{sc}}{\partial T} = 0.53 \cdot 10^{-3} \text{K}^{-1}$ and $\frac{1}{FF}\frac{\partial FF}{\partial T} = 3.36 \cdot 10^{-3} \text{K}^{-1}$ are determined by modeling [5]. The thin-film silicon-based solar cell with nanoparticle is found to increase the temperature coefficient by 9 %.

4. CONCLUSIONS

The effect of metal nanoparticles on the photoelectric parameters of a thin-film silicon-based solar cell was found to be significant. In conclusion, from the above results, it was found that it is preferable to add titanium and platinum materials to silicon-based solar cells as nanoparticles. The fact that different nanoparticles affect the temperature coefficients of different parameters of a silicon-based solar cell proves that nanoparticles have an effect on the electrophysical properties of silicon material. This means that nanoparticles can be widely used not only in solar cells, but also in other types of electronic and optoelectronic silicon-based devices. For example, a device for measuring temperature can be made from silicon with silver nanoparticles. It is 6 times more sensitive than existing silicon-based temperature sensors.

Table 2 – Temperature coefficients of the main photoelectric parameters of NISCs and an SSC

	$\partial U_{oc}/U_{oc}\,\partial T$, [1/K] × 10^{-3}	$\partial I_{sc}/I_{sc}\,\partial T$, [1/K] × 10^{-3}	$\partial U_m/U_m\,\partial T$, [1/K] × 10^{-3}	$\partial J_m/J_m\,\partial T$, [1/K] × 10^{-3}	$\partial P_m/P_m\,\partial T$, [1/K] × 10^{-3}	∂FF/FF ∂T, [10^{-3}/K] × 10^{-3}
–	4.216	0.13623	4.778	0.712	5.152	1.498
Cu	4.216	0.789	4.778	1.414	5.519	1.583
Au	4.314	0.783	4.889	1.282	5.546	1.497
Ag	4.356	0.853	4.944	1.419	5.661	1.593
Al	4.272	0.871	4.778	1.442	5.530	1.456
Co	4.356	0.604	4.944	1.092	5.498	1.510
Pt	4.095	0.761	4.565	1.373	5.311	1.406
Ti	4.095	0.727	4.565	1.312	5.278	1.381

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Вивчення температурного коефіцієнта основних фотоелектричних параметрів кремнієвих сонячних елементів з різними наночастинками

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Підвищення ефективності параметрів тонкоплівкових сонячних елементів є важливою задачею. Існує декілька методів покращення оптичних та електричних властивостей сонячних елементів на основі плівок кремнію. При впровадженні металевих наночастинок в плівку кремнію змінюються параметри сонячного елемента та їх температурні коефіцієнти. У роботі представлені результати дослідження впливу наночастинок Au, Ag, Pt, Ti, Co, Al і Cu на температурний коефіцієнт фотоелектричних параметрів тонкоплівкового сонячного елемента на основі кремнію, які були розраховані в температурному інтервалі від 250 до 350 К. Установлено, що напруга холостого ходу сонячного елемента з наночастинками Pt і Ti змінюється на 0,4 % при зміні температури на 1 К. Крім того, показано, що струм короткого замикання сонячного елемента з наночастинками Ag зростає в 6,3 рази.

Ключові слова: Моделювання, Наночастинка, Сонячний елемент, Кремній, Температурний коефіцієнт.