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The Way of the Increasing Two Times the Efficiency of Silicon Solar Cell

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Increase of the efficiency of the solar cells which are produced in industry, is important. Increase of efficiency of solar cells was identified, when nanoplasmonics phenomenon was formed in solar cell. So, in this article, influence of nanoparticles Pt, Au, Ag and Cu on properties of silicon based solar cell has been studied. When nanoparticle Pt was inclused in silicon based solar cell, its efficiency increased 2.31 times. Short circuit current of its is increased 2.23 times as well as open circuit voltage is increased 1.05 times. Optimal radius of Pt nanoparticle was identified to be between 15-25 nm.

Key words: platinum, silicon, solar cell, nanoparticle, modeling.

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Introduction

Nowadays a lot of research works are being done, in order to increase efficiency of solar cell. There are a lot types of solar cells, including silicon based solar cells, which are produced at the industry level [1]. Maximum theoretical efficiency of the silicon based solar cell was calculated by Shokley Quisser, according to this calculation, efficiency was 29% [2]. But, maximum theoretical efficiency of nanostructured silicon based solar cell was theoretically calculated to be 42% by Yunlu Xu [3]. Optical and electrical properties of solar cell need to be improved, in order to increase its efficiency. For example, by the forming textures on the surface of the solar cell, efficiency of silicon solar cell increases 1.26 times [4]. Besides, the efficiency of silicon solar cells can be enhanced by using plasmonic effect [5]. First time, the nanoplasmonic effect was observed in Noble nanoparticle and efficiency of energy conversion was increased [6]. In our previous researches, we identified that nanoplasmonic effects are appeared when the other metal nanoparticles are input into silicon solar cells [7]. So, in this paper, influence of Ag, Au, Cu and Pt nanoparticles on efficiency of silicon based solar cell has been studied.

I. Method

Nanoparticles introduced silicon solar cell (NISSC), are simulated by using Sentaurus TCAD. Four different metals were selected as nanoparticles, these are Au, Ag, Cu and Pt. In Figure 1, nanoparticles were introduced in n region of solar cell. Solar cell has symmetry, so 2D geometric model has been developed. Sentaurus TCAD has 23 tools. But, only fours of them are used to simulate solar cells. These are Sentaurus Structure Editor, Sentaurus Device, Sentaurus Visual and Sentaurus Workbench. Sentaurus Structure Editor was used, in order to create a geometric model. In this tool, unique algorithm was developed to create nanoparticles with changeable number, size and inputting place by using Tool Command Language.

After creating geometrical model of solar cell, physical properties were given then calculations were performed by using Sentaurus Device. Physical properties of all materials were uploaded to model as a parameter file. Physical models were added to simulation by writing the code in the Sentaurus Device command file.

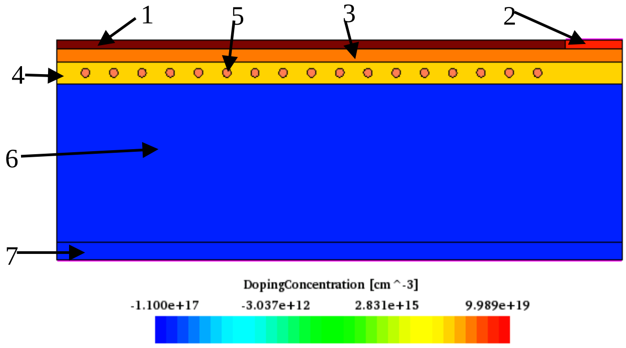

Fig. 1. Geometric model of NISSC: 1 – optical layer, 2 – front contact region, 3 – n++ region, 4 – n region, 5 – metal nanoparticle, 6 – p region, 7 – p++ region.

The simplest state among the processes, which are occurred in the semiconductor devices, is equilibrium state. In this state, at least Poisson equation, which is shown in formula (1), must be solved.

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

Where: ε – permittivity, n and p – concentration of electron and holes, N_D and N_A – donor and acceptor concentration, q – electron charge.

Electron concentration n as well as hole concentration p are calculated by using Fermi distribution that is shown formula (2) and (3).

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

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

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

Optical properties of solar cells should be calculated in order to simulate them completely. Because, solar cells are also optical devices. In this paper, Transfer Matrix Method (TMM), which was shown formula (4), has been used to calculate optical properties of NISSC. Because, TMM can take into account interference phenomenon as well as it can be used in modeling thin film solar cells.

$$\begin{bmatrix} E_i \\ E_2 \end{bmatrix} = M \begin{bmatrix} E_t \\ 0 \end{bmatrix} \tag{4}$$

Where: M – transfer matrix, E_i – the electric field of the incident light, E_r – the electric field of the reflected light, E_t – the electric field of the transmitted light.

Boundary conditions must be declared for each interface between regions. In the TMM, a boundary condition can be defined through calculating by using the Fresnel coefficients. In this model, the boundary conditions, which are set between the air and texture of silicon, were identified through the Fresnel's laws:

$$\begin{cases} r_\perp = \dfrac{n_1\cos\alpha - n_2\cos\gamma}{n_1\cos\alpha + n_2\cos\gamma} \\ t_\perp = \dfrac{2n_1\cos\alpha}{n_1\cos\alpha + n_2\cos\gamma} \end{cases}, \tag{5}$$

$$\begin{cases} r_\parallel = \dfrac{n_1\cos\gamma - n_2\cos\beta}{n_1\cos\gamma + n_2\cos\beta} \\ t_\parallel = \dfrac{2n_1\cos\beta}{n_2\cos\beta + n_1\cos\gamma} \end{cases}, \tag{6}$$

where: n_1 and n_2 are the refractive indices of mediums; β – the angle of incident light; γ – the angle of refracted light; *r* and *t* – the Fresnel coefficients.

Transportation of carriers is occurred due to external applied voltage, illumination or heating. In these phenomena, equilibrium state is broken up. Due to solar cells are illuminated, them also carriers transport should be calculated during simulation. Motion of carriers forms current. Basically, connection between carrier concentration and current density is expressed by "general continuity equations" which are shown in formula (7) and (8).

$$\nabla \cdot \vec{J}_n = qR_{net,n} + q\frac{\partial n}{\partial t} \tag{7}$$

$$-\nabla \vec{J}_p = qR_{net,p} + q\frac{\partial p}{\partial t} \tag{8}$$

Where: J_n, J_p are the current densities of electron and holes, $R_{net,p}$, $R_{net,n}$ are the net recombination of electron and holes, t - time

In Sentaurus Device, "Drift-Diffusion", "Thermodynamic", "Hydrodynamic" and "Monte Carlo" models are used to calculate carrier transport. "Thermodynamic" model, which is given formula (9) and (10), have been used to model solar cell. Since, generation and recombination rate of carriers is changed when light intensity is changed. Besides, heat energy or phonons concentration can be changed. Therefore, heat energy, which is formed due to motion of carriers, also changed. All of them have been taken into account in "Thermodynamic" models.

$$\vec{J}_n = -nq\mu_n(\nabla\Phi_n + P_n\nabla T) \tag{9}$$

$$\vec{J}_p = -pq\mu_p(\nabla\Phi_p + P_p\nabla T) \tag{10}$$

Where: μ_n, μ_p are mobility of electron and holes, Φ_n, Φ_p are the electron and hole quasi-Fermi potentials, P_n,

P_p are thermoelectric power of electron and holes, T is absolute temperature.

Formula (11) has been used to calculate carriers transport in metal nanoparticles.

$$\vec{J}_M = -\sigma(\nabla\Phi_M + P\nabla T) \quad (11)$$

Where: σ is conductivity of metal, Φ_m is Fermi potential in metal, P is the metal thermoelectric power, J_M is current density in the metal.

It has been considered that there were ohmic boundary conditions between metal nanoparticles and silicon interface, due to nanoparticles input into n region of silicon solar cell. Ohmic boundary conditions were calculated by formula (12).

$$\begin{aligned} &\vec{J}_M \cdot \hat{n} = (\vec{J}_n + \vec{J}_p + \vec{J}_D) \cdot \hat{n} \\ &\phi = \Phi_M - \Phi_0 \\ &n = n_0 \\ &p = p_0 \end{aligned} \quad (12)$$

Where: J_D is diffusion current density, $\hat{n}$ is normal vector, Φ_0 is the equilibrium electrostatic potential (the built-in potential), ϕ – electrostatic potential, n_0, p_0 are the electron and hole equilibrium concentrations.

Due to numerical methods are utilized to simulate semiconductor devices in Sentaurus TCAD, the after creating geometric model, whole model is meshed with acceptable sizes. In this work, the NISSC has been meshed with 0.004 μm along x axis and 0.002 μm along y axis.

II. Results and discussion

Two types phenomenon are observed when nanoparticles are illuminated. First, nanoparticle absorbs the infrared and emits light which is in visible light spectrum. Second, resonance phenomenon is observed when vibration frequency of electrons in nanoparticle is equal to frequency of the electromagnetic wave. So, electrons emit from the nanoparticle. Mainly, nanoparticles are introduced into dielectric layer of solar cell. Therefore, only changing the spectrum of light by nanoparticles helps to increase efficiency of solar cell not resonance phenomenon. We thought the inputting of nanoparticles into n region of silicon solar cell give chance to use resonance phenomenon in addition to changing the light spectrum. In our previous scientific works, it was found that its efficiency is good when size of the nanoparticle is 15-20 nm [8], [9]. In figure 2, dependence of absorption coefficient of Au, Ag, Cu, Pt NISSCs and SSC on wavelength are shown. At 0.5 μm of light wavelength, absorption coefficient of all type NISSCs, which are included Au, Ag, Cu or Pt, has been increased than that of SSC. In the Bonaccorso's experiment, resonance of absorption coefficient of gold with 10-30 nm radius is occurred at 0.5 μm of wavelength [10]. But it was found that absorption coefficient of Pt NISSC at 0.5 μm of wavelength and infrared spectrum has been better than that of other type NISSCSs and SSC. The minimum absorption coefficient was observed in silicon based solar cell which is included the silver nanoparticle.

Photoelectric parameters of solar cell are determined through I-V characteristic of solar cell. In figure 3, I-V characteristic of SSC and Pt, Ag NISSCs, is described. Short circuit current of SSC is 4.88 mA/sm^2, because its thickness is 1 μm. Short circuit current increases 2.23 times, when nanoparticle Pt was input into n region of silicon solar cell of the same thickness. In the Bao's experimental work, short circuit current of Pt introduced silicon solar cell was increased 2.28 times than that of silicon solar cell [11]. In the Kuing-Qing Peng's experimental work, efficiency and the short circuit current was increased to 8.17%, when surface of solar cell was covered with the Pt nanoparticle with a radius of 5-10 nm [12]. The short circuit current decreases 1.34 times, when the silver nanoparticle was introduced into the solar cell.

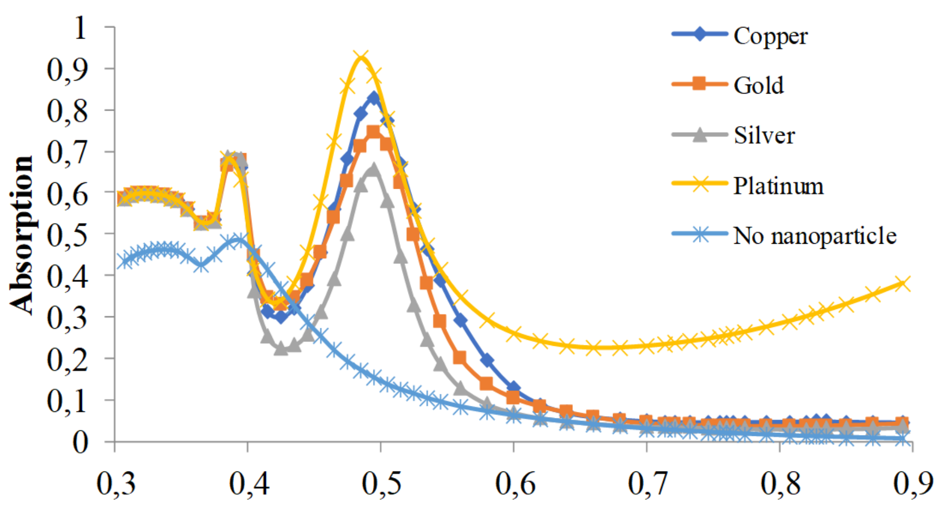

Fig. 2. Dependence of absorption coefficient of silicon solar cell (SSC) and Cu, Au, Ag, Pt NISSCs on light wavelength.

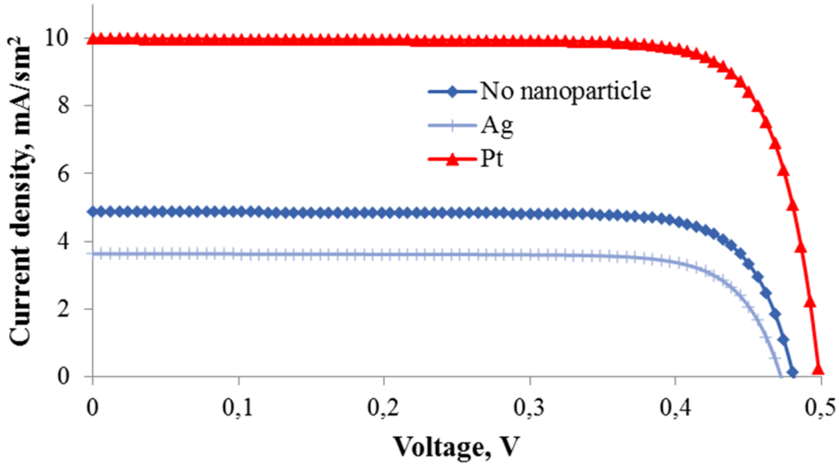

Fig. 3. I-V characteristics of SSC and Ag, Pt NISSCs.

The similar result was observed in experimental work which was conducted by Tayyar Zafar, according to its, the short circuit current of the solar cell is decreased, when nanoparticle Ag was introduced into silicon solar cell [13]. Because, the phase difference of electromagnetic wave, which was formed by the silver nanoparticles, is between (π: π/2), so interference minima are occurred. This phenomenon was called Fano interference [14].

Conclusion

In conclusion, we should pay attention to material, size of nanoparticles and distance between nanoparticles which are input into solar cell. Because, nanoparticles may have effect on the efficiency of solar cell. Maybe, optimal condition of nanoparticles is different for solar cells, which are formed from various materials. Our simulation results have been acceptable to experimental results which were conducted by other scientists. In this paper, introducing of Pt nanoparticles into n region of silicon solar cell gives good results. In our simulation, it was found that Pt nanoparticles can increase 2.3 times the efficiency of silicon solar cell. So, we think, Pt nanoparticles have effect on properties of silicon material. Because, Pt nanoparticles affect on open circuit voltage of silicon solar cell. Open circuit voltage especially depends on carrier concentration or band gap energy. So, the silicon which included nanoparticle, is used to make not only solar cells, but also other semiconductor optoelectronic devices.

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Шляхи щодо підвищення ефективності кремнієвих сонячних елементів вдвічі

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Важливим є підвищення ефективності сонячних елементів, які виробляють промислово. Показано, що спостерігається підвищення ефективності сонячних елементів при реалізації наноплазмонних явищ. У цій статті досліджується вплив наночастинок Pt, Au, Ag та Cu на властивості кремнієвої сонячної батареї. При введенні у сонячний елемент на основі Si, наночастинки Pt, його ефективність зростає в 2,31 рази. Струм короткого замикання збільшується в 2,23 рази, а напруга холостого ходу – в 1,05 раз. Оптимальний радіус наночастинки Pt визначений як 15-25 нм.

Ключові слова: платина, кремній, сонячний елемент, наночастинка, моделювання.