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Light Absorption Improvement in Si Thin Film Solar Cells Using Combination of Graphene-based nanoparticle and strips-grooves geometry

Hasan Kanani [1], Saeed Golmohammadi [2], Hasan Rasooli Saghai [*,3], Jaber Pouladi [1]

[1]Department of Electrical Engineering, Shab.C., Islamic Azad university, Shabestar, Iran

[2]Department of Electrical and Computer Engineering, University of Tabriz, Tabriz, East Azarbaijan, Iran

[3]Department of Electrical Engineering, Ta.C., Islamic Azad University, Tabriz, Iran

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Abstract:

Excitation of surface plasmon polariton (SPP) in Sub-wavelength dielectric/metal structures is a key to enhance the light absorption of thin film solar cells (TFSCs). We design a SiO_2/Ag nanostructured grooves geometry at the rear-side of a Si-based TFSC to excite SPPs. This geometry scatters light inside absorber layer in many directions resulting in absorption enhancement. In addition, we consider SiO_2 corrugated strip geometry at the top of the absorber layer as light trapping technique. The height and width of the SiO_2 strips are 60 nm and the height and width of the grooves are 30 nm. We apply this technique in the Si-based TFSC that contains Ag/graphene nanoparticles (NP-TFSC) in absorber layer as localized plasmon resonance elements. The thickness of absorber layer is 800 nm. We simulate this TFSC utilizing FDTD method. Results of simulations reveal a 21.36% absorption enhancement, a 16.39% J_{sc} increment and a 3.9% in conversion efficiency improvement.

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***Corresponding author:** Hasan Rasooli Saghai
Address: Department of Electrical Engineering, Tabriz Branch, Islamic Azad university, Tabriz, Iran. ***Tell:*** *00989143156503* ***Email:*** *h_rasooli@iaut.ac.ir*

1. INTRODUCTION

Solar cells are promising eco-friendly energy source to decrease fossil fuels consumption [1]. Solar cells on basis of crystal silicon (Si) have been commercialized widely due to the great abundance of Si and the well-developed process [2, 3]. Although crystal Si-based solar cells hold the world record in efficiency, researchers have focused on thin film solar cells (TFSCs) as suitable replacements with lower production cost [4]. TFSCs enable reduced cost by replacing the bulk substrate with 1-2μm thin film layers. But this thin film results in ineffective light absorption due to the short light pathway [5].

Several techniques have been proposed by pioneer researchers to boost the light absorption of TFSCs including using of anti-reflection coatings, window grids, photonic crystals, and plasmonic nanoparticles [6-8]. Plasmonic nanoparticles that are embedded inside of the absorber layer, scatter light in many directions resulting in electrical field enhancement and more electron-hole pair generation [9, 10]. This is because of the fluctuation of their free electrons under irradiation of the incident light. If the frequency of the incident light is the same as the fluctuation frequency of nanoparticle free electrons, the localized surface plasmon resonance (LSPR) will occur [11].In our pervious study, we have introduced a core/shell silver (Ag)/graphene plasmonic nanoparticle related to this category. In that study, we embedded the Ag/graphene nanoparticle inside the active layer of a Si-based TFSC resulting in a 20.6% increase in absorption and a 7.3% rise in short-circuit current density [12].

Along abovementioned techniques, subwavelength plasmonic structures have a great potential to increase the light absorption in TFSCs. The increased absorption is possible through excitation of surface plasmon polaritons (SPPs) in corrugated subwavelength structures [13]. SPP arises from the interaction between the incident light and fluctuations of free electrons in subwavelength structures [14, 15]. Nanostructured grooves at the rear-side of a TFSC excite SPP modes resulting in light scattering and internal electrical field enhancement [16].

Cao et al. have used a nanostructured metal layer based on Ag at the rear-side of an a-Si TFSC to facilitate an increased optical path length within absorber layer. They have reported a power conversion equal to 7.26% [17]. Awal et al. have proposed a Si-TFSC with strips on the top and grooves on the back contact layer. The grooves on the back contact both scatter the incident light and help couple to the photonic modes and resonant SPP. They have achieved an increase of 46% in light absorption compared to a planar TFSC [13]

Sidharthan et al. have designed a Si-TFSC with nanostructured grating at the rear-side as SPP element and Ag nanoparticles inside absorber layer as LSPR elements. They have reported a 14.4% increment in short circuit current density (J_{sc}) compared to the planar solar cell [18]. Prabhathan et al have proposed a SPP waveguide at the rear-side of a Si-TFSC to light absorption enhancement. Absorption enhancement of 153% was observed for a Si-TFSC with the thickness of 220 nm for absorber layer in the solar spectral range of 400nm to 1000nm [16].

In this study, we propose a light absorption enhancement technique using combination of SPP and LSPR effects for TFSC applications. We utilize nanostructured grooves in the interface of back metal contact and a dielectric at the rear-side of a Si-TFSC to excite SPP effect. At the top of the TFSC, we design corrugated strip geometry for light trapping. We embed Ag/graphene nanoparticles inside the absorber layer of the TFSC to excite LSPR. We design and simulate the TFSC through finite-difference time-domain (FDTD) method using Lumerical software while the permittivity of Ag/graphene nanoparticle is computed numerically through Kubo formalism.

2. Material and method

Figure 1 depicts the proposed TFSC configuration. This configuration consists of corrugated strips of SiO_2 with the thickness of 60 nm and width of 60 nm, a Si absorber layer with the thickness of 800 nm, and a Ag back contact with the thickness of 150 nm. We locate a dielectric/metal SiO_2/Ag nanostructured grooves geometry at the rare-side of the TFSC to excite SPP effect. Both thickness and width of the grooves are 30 nm. We embed the Ag/graphene nanoparticles inside the absorber layer with the distance of 100 nm from the top of the cell to excite the LSPR effect. These cylindrical nanoparticles consist of an Ag core with the diameter of 50 nm and height of 50 nm that is covered with a graphene layer with the thickness of 0.8 nm. The whole of structure is doped by p-type impurity with the concentration of 2×10^{16} 1/cm^3 and a n-type impurity is considered at the back of cell with the thickness of 100 nm while beneath of the emitter is doped by a p++ impurity with the concentration of 2×10^{20} 1/cm^3 and thickness of 50 nm. The structure of the Si-TFSC is irradiated by a source of plane wave in the spectral range of 400 nm to 1000 nm in the direction of Z. We set the periodic boundary conditions along X and Y directions and PML boundary condition along Z direction. Finally, we use the "solar generation rate solver" for optical simulation.

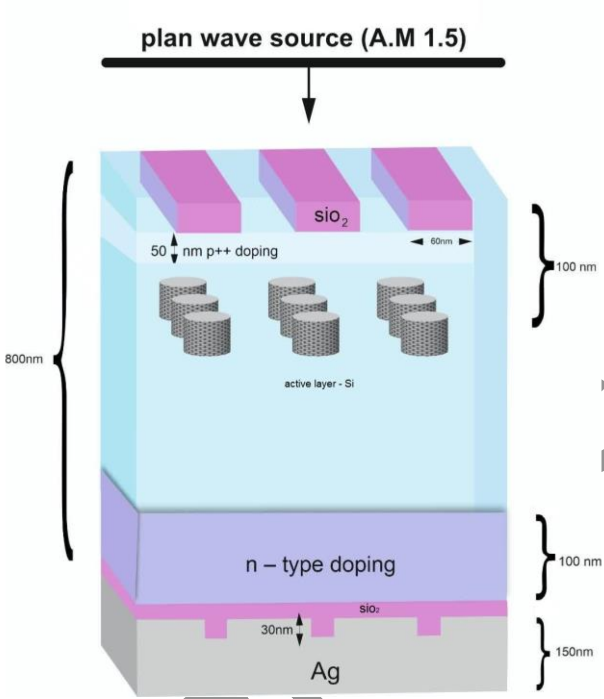

Fig. 1. The proposed Si-TFSC configuration

We calculate the dielectric permittivity of the Ag/graphene nanoparticle through $\varepsilon_{np} = f \times \varepsilon_{eq-G} + (1-f)\varepsilon_{Ag}$, where ε_{np} is the dielectric permittivity of nanoparticle, f is the volume fraction of graphene and ε_{Ag} is the dielectric constant of silver based on Johnston-Christy model. ε_{eq-G} is the permittivity of graphene and is computed through $\varepsilon_{eq-G} = 0.83 + 0.66(2.5 + i\sigma(\omega)/0.8\omega)$, where ω is the frequency of incident light and σ(ω) is the surface conductivity of the graphene layer [12, 19]. σ(ω) is obtained by interband and interaband terms [20] based on Kubo formalism through:

$$\sigma = \frac{i2e^2k_BT}{\pi\hbar^2\left(\omega + i\tau_G^{-1}\right)} + \frac{e^2}{4\hbar}\left[\frac{1}{2} + \frac{1}{\pi}\arctan\left(\frac{\hbar\omega - 2E_f}{2k_BT}\right) - \frac{i}{2\pi}ln\frac{\left(\hbar\omega + 2E_f\right)^2}{\left(\hbar\omega - 2E_f\right)^2 + 4k_B^2T^2}\right] \quad (1)$$

Where, e, k_B, $\hbar$, T, E_f, τ_G are the electron charge, the constant of Boltzmann, the reduced constant of Planck, the temperature, the graphene Fermi level, and the graphene carrier relaxation time (1fs) respectively [21-23].

Base on Poynting Theory, the solar cell absorption is calculated through equation:

$$P_{abs} = -0.5\omega |E|^2 \, img(\varepsilon) \tag{2}$$

Where ω, |E| and img (ε) are angular frequency, the intensity of electric field, and the imaginary part of the permittivity, respectively [24, 25]. We run our simulation under standard normalized spectrum AM 1.5. So the solar generation rate (G) and short circuit current density (J_J) are obtained via following equations:

$$G(z) = \int_{400\,nm}^{1000\,nm} \frac{P_{abs}}{hc/\lambda} d\lambda \tag{3}$$

$$J_{sc} = e\int_{400\,nm}^{1000\,nm} \frac{\lambda}{hc} \frac{P_{abs}}{P_{in}} I_{AM.1.5}(\lambda) d\lambda \tag{4}$$

where, h is constant of Plank, c is the light speed, λ is wavelength, P_{in} is the irradiated light power, and $I_{AM1.5}$ is AM 1.5 solar spectrum [25-27].

3. Results and discussion

In our pervious study, we have reported a 20.6% increment in overall absorption at the spectral range of 400-1000 nm and a 7.3% rise in J_{sc} for TFSC with Ag/graphene nanoparticle (NP-TFSC). These improvements have been obtained in comparison with the same TFSC without Ag/graphene nanoparticles [12]. The gap between nanoparticles is 100 nm that was optimized based on J_{sc}. Fig.2 depicts the variation of J_{sc} versus the gap between nanoparticles. When there is a less than 100 nm gap, due to the shadow effect as a result of the increase of density of nanoparticles, J_{sc} decreases. On the other hand, for gaps more than 100 nm there is a performance deterioration because of weakening of the aspects of plasmonic effect such as near-field enhancement.

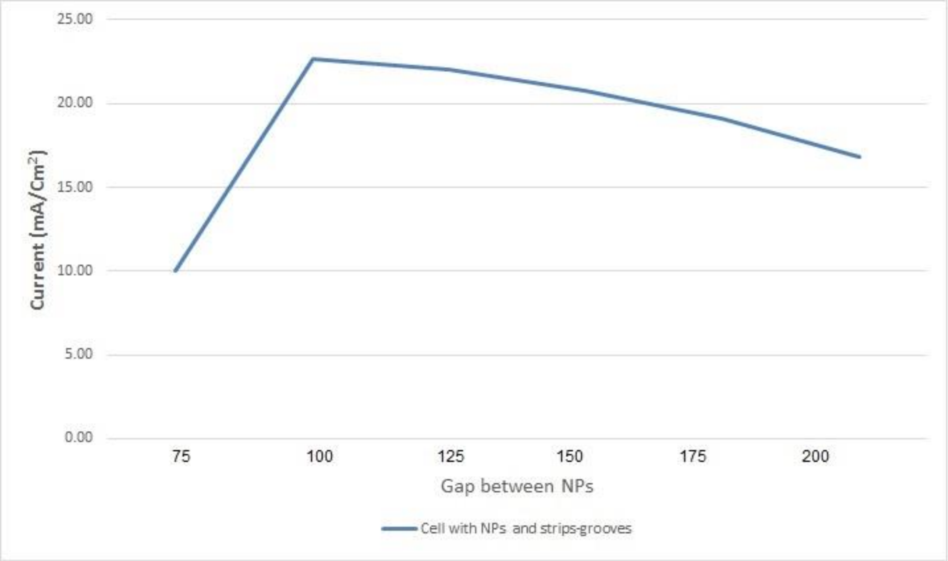

Fig. 2. variation of J_{sc} versus the gap between nanoparticles

In order to perform a comparative analysis of absorption and J_{sc}, we compare the TFSC of this study with the NP-TFSC. Figure 3, compares the absorption profile of NP-TFSC and TFSC with nanoparticle and strips and grooves geometry (SG-NP-TFSC). The integration process was performed on both curves depicted in Fig.3 through the utilization of Origin software. The computed integrals for NP-TFSC and SG-NP-TFSC amounted to 19651 and 23850 respectively. So the absorption of TFSC improves 21.36% utilizing strips and grooves geometry.

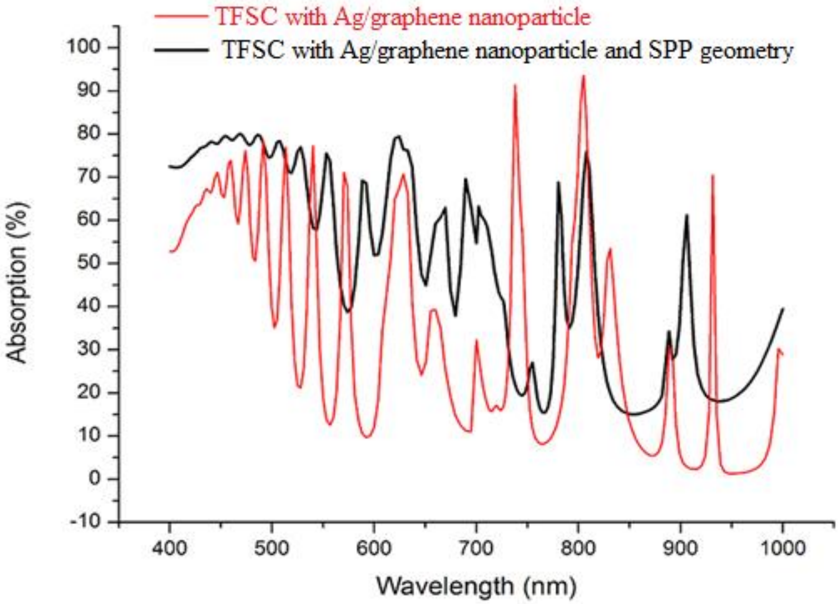

Fig. 3. The absorption profile of of TFSC with Ag/graphene nanoparticle and TFSC with strips and grooves geometry

J_{sc} of the SG-NP-TFSC is computed 22.70 mA/cm^2. In comparison with NP-TFSC with J_{sc} of 19.503 mA/cm^2, J_{sc} improves 16.39% due to excitation of SPP. Figure 4 presents the voltage-current diagram and figure 5 presents voltage-power diagram for NP-TFSC and SG-NP-TFSC. Based on the outcomes that are achieved from this diagram the conversion efficiency of NP-TFSC and SG-NP-TFSC are computed 12.1% and 16% respectively. It means that the applying of the strip and grooves geometry enhance the conversion efficiency 3.9% due to excitation of SPP.

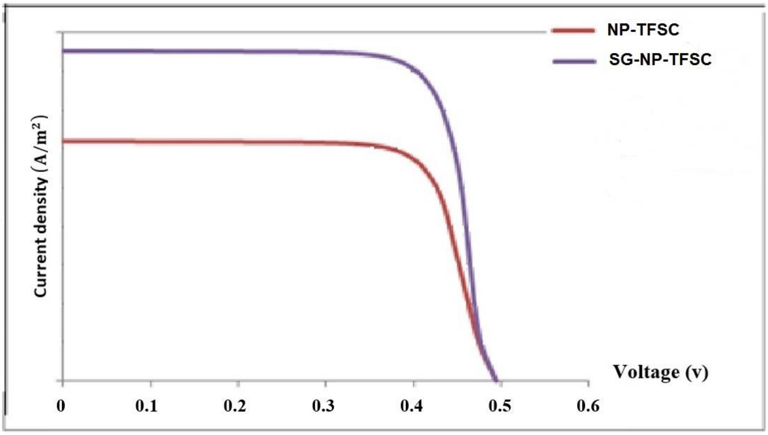

Fig. 4. Voltage-current diagram for NP-TFSC and SG-NP-TFSC

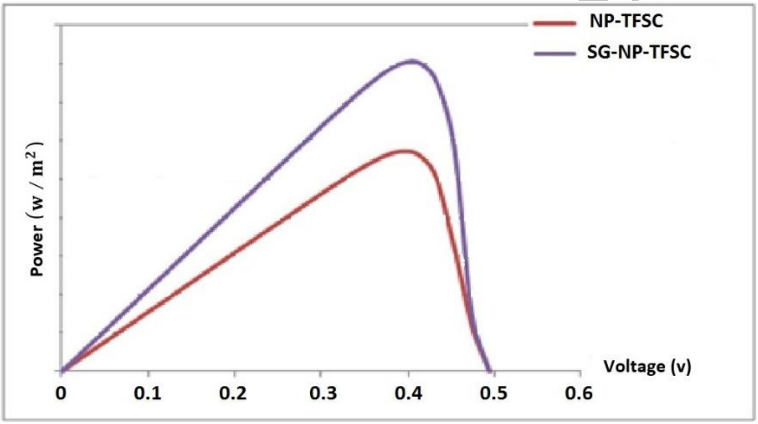

Fig. 5. Voltage-power diagram for NP-TFSC and SG-NP-TFSC

Tab. 1 provides a reference for comparison of the output of our study with other similar researches. It should be noted that the enhancements that are reported in Tab. 1 are in compared with the base cell without nanoparticles, groves and strips. For our study the J_{sc} of base cell is 15.11 mA/cm^2.

Tab.1 Comparison of the outputs of our study with similar researches

Solar cell absorber layer/nanoparticle	J_{sc} (mA/cm^2)	Enhancement of J_{sc}	Absorption enhancement	Ref.
Si/NPs at top with strips and grooves (our study)	22.7	50.23%	45.26%	
Si/with grooves and strip	19.1			[28]
a-si/ (sio2@Ag(Hemisphere) NPs	19.72	21%	-	[29]
Si/(Ag@sio2) NPs	6.91			[30]
Si/(Ag@Dielectric) NPs				[31]
Si/(graphen@Ag) NPs	20.05	35%	29%	[11]

4. Conclusion

In this research, we have designed a Si-based TFSC with strips at the top of the absorber layer and SiO_2/Ag nanostructured grooves geometry at the rear-side of the absorber layer while Ag/graphene nanoparticles are embedded inside the absorber layer. We have considered the corrugated strips as light trapping structure, nanostructured grooves geometry as SPP element and Ag/graphene nanoparticles as LSPR elements. In comparison with TFSC with nanoparticles, adding of the strips and grooves results in a 21.36% absorption enhancement, a 16.39% J_{sc} increase and a 3.9% conversion efficiency improvement.

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