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Enhancement of Silicon Solar Cell's Performance using Plasmonic Ag Nps

Abstract- In this paper, Silver nanoparticles (Ag NPs) were prepared by laser ablation in liquid (PLAL) technique for different laser energy in water. Then the Ag NPs were deposited on the surface of Si solar cells to enhance their plasmonic absorption. The UV-VIS, FTIR spectrometer, and the Atomic force microscope were used to study the optical properties, composition, and the surface morphology of the NPs, respectively. The atomic absorption spectroscopy was also used to find the amount of ablated material. It is found that after the thermal deposition of the water drops containing Ag NPs on the surface of Silicon solar cells, the short circuit current and the overall conversion efficiency (η) have been improved. The short circuit current density (J_{sc}) has been increased by 14% after the drop overcasting of Ag NPs (about 92 nm in size) on the surface of silicon solar cells. The relative increase in J_{sc} may be attributed to the enhance plasmonic absorption for the incident light due to the forward scattering of Ag NPs.

Keywords- Silicon solar cell, laser ablation, Ag NPs, plasmonic absorption.

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1. Introduction

Photovoltaic solar cells can supply electric power by transforming sunlight into electrical energy [1]. Silicon (Si) is the common that was used in most common photovoltaic applications [2] due to its low cost, abundance in nature, nontoxicity, long-term stability, and well-established technology [3]. However, Si has relatively high absorption depth, which is not convenient for thin film solar cells. It has been shown that a noble metal NP with plasmonic effects can significantly enhance the light absorption and consequently the conversion efficiency of the photovoltaic devices [4-6]. This is for the large free electron density of metals [6], which can have strong interactions with visible light leading to surface plasmon resonances (SPR) [7]. Plasmonic NPs can either enhance or suppress photocurrent in the device depending on wavelength, NP resonance, and nanostructure size and geometry [8]. By virtue of SPR, sunlight can be captured and trapped in hence increase absorption intensity [9]. Typically, forward scattering and SPR using metallic NPs (e.g. gold, silver, and aluminium) can enhance the optical transition rate in the material due to the enhanced generation of electron-hole pairs [1, 10]. Both silver and aluminum NPs have analogues influences on the photocurrent of the GaAs solar cells. Scattering to absorption ratio is increased by increasing the NP-size near the SPR [11]. The ability of NPs to enhance

scattering, fluorescence and emission has been proved by many researchers [7-13]. The idea of increase absorption using NPs has found applications in optoelectronic devices. For example, an increase in the J_{sc} of a-Si:H solar cells was achieved using Au NPs with particle size from 50 to 100 nm. Several researchers reported that the scattering effects predominate for large particle size (>100nm) while absorption effects are dominant for smaller nanoparticles (<50nm) and this property is appropriate for photovoltaic applications [4,14,15]. Jana et al. [2] have reported plasmonic enhancement using colloidal NPs. Pillai et al. [3] showed significant enhancement in electroluminescence from silicon-on-insulator light-emitting diodes via using Ag NPs. Derkacs et al. [16] observed an enhancement of about 8 % and 8.3% on the J_{sc} and the conversion efficiency respectively in p-i-n solar cells. Matheu et al. [16] observed an enhancement in the conversion efficiency of about 2.8% for Silicon devices using 100 nm Au colloidal particles and 150 nm silica particles, respectively. Ouyang et al. [17] showed an enhancement in photocurrent and conversion efficiency for thin-film Si cells deposited on glass due to plasmonic light trapping. Moulin et al. [18] illustrated an increased in light absorption and enhanced photocurrent in wavelength range (600-1150 nm) in presence of NPs. Lare et al. [19] revealed that there is strong interaction between Ag

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NPs array and the surface of thin film solar cell made from amorphous silicon (a-Si). Spectral enhancement the photocurrent (about 10%) in the spectral range 450-750 nm. Starowicz et al. [4] demonstrated an increase of about 5 % in short circuit current (I_{sc}) for solar cells with uniformly sized Ag NPs (about 70 nm) buried in TiO thin films, which is used as cell antireflection coating. Cai et al. [20] proposed to invest the plasmonic near-field light concentration in a-Si solar cells by using few nanometers of Au NPs placed on the surface of the solar cells at the interface between the transparent conductive oxide and the Si-layer. Enhancements in the photocurrent (14.1%) is achieved. Al-Azawi et al. [13] prepared Ag NPs using laser ablation technique and showed the feasibility of obtaining small Ag NPs (particle size 4.3-15 nm) with maximum efficiency at liquid about 14 mm. In this paper, we study the role of using Ag NPs on the performance of silicon solar cells.

2. Experimental Part

First, the Si-solar cell was dipped into solution of hydrofluoric acid and deionized water (1:10) for 1 min to remove the original antireflection coating and to remove any contamination on the front side of the silicon solar cells. The silicon solar cell samples then immersed in deionized water to remove the remaining hydrofluoric acid and then they have been set to dry. The silicon solar cell samples were cut into small pieces using diamond cutter. Silver colloidal was prepared by PLAL technique (Figure 1) at different fluences 2.94 J/cm², (b) 5.88 J/cm², (c) 8.82 J/cm², (d) 11.76 J/cm² and using water as a solving liquid. Ag pellet is used as a target in our setup. After their preparations, the Ag NPs was deposited onto the surface of silicon solar cell by drop overcasting method i.e., dropping the Ag colloidal solution onto the surface of hot solar cell (80 oC) and finally it is set to dry. Current-voltage measurement was achieved by Si-solar cell illumination using light source (tungsten halogen lamp) of 100 mW/cm². The power of the tungsten lamp was already normalized with a xenon lamp used in a standard atmospheric system. The absorbance spectra were measured by UV VIS single beam spectrophotometer. Absorbance spectra were measured at RT in quartz containers of 1 cm thickness. Another quartz cuvette filled of deionized water was used as a background reference.

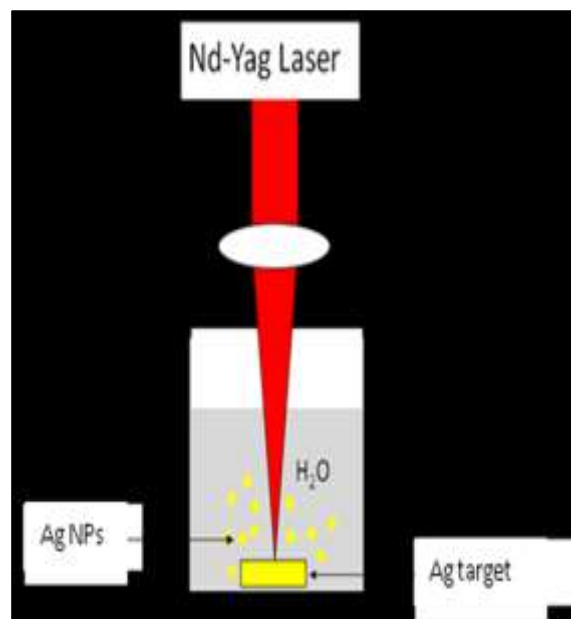


Figure 1: Pulsed laser ablation in liquid (PLAL) technique

PLAL experiments are carried out in liquid mediums such as water and ethanol. The laser pulses produce plasma [21,22]. The plasma tends to expand at a supersonic velocity. However, this expansion creates a shock wave because the liquid confines the expansion of plasma. The laser pulses impinging on the solid target generate a continuous supply of ablated material in the plume; this is the source of the plasma intense luminosity. In fact, the vaporizing species are highly excited ionic particles, that incoherently relax towards fundamental quantum states emitting electromagnetic radiations. There are three thermodynamic factors that determine the nature of phases in the plasma. These parameters are: (1) density of ablated species, (2) temperature and (3) pressure in the plasma. In the real experiments, the plume shape tends to be hemispheric of diameter about 100 μm [23]. The plume temperature may reach 5000 K [23]. The shock wave induce in the plasma plume extra conditions of pressure temperature and density. The pressure may take an order of several GPa. From Berthe's studies [24-25], an equation for the extra plasma pressure in GPa unit is given by: is the internal energy fraction (of the order 0.25), I_0 (GW cm⁻²) is the intensity of incident power, and Z (g cm⁻² s⁻¹) is the shock impedance between the solid target and the surrounding liquid medium. When the liquid medium is water, Z is given by the relationship [23-25]. The concentration of NPs was measured by

Atomic Absorption Spectroscopy, Phonex 986AA. Standard solutions of AuNO_3 , AgNO_3 were used to establish the relation between the measured absorbance and the analytic concentration. The surface morphology and size distribution of the Ag NPs were examined by Atomic Force Microscopy. The test samples were made by putting a drop of the Ag colloidal on a silicon substrate. The drop was dried with a normal tungsten heater until all the colloidal had evaporated.

3. Result and Discussion

Figure 2 shows different colors, which belongs to different laser fluencies of the colloidal Ag NPs in deionized water. It is found that the opacity of these colloids increases with increasing of the laser fluence. The opacity is proportional to the concentration of Ag NPs in water. The color of silver solution ranges from yellow to yellow-brown.

Figure 3 shows the typical absorption spectra of Ag colloidal solutions at various laser fluencies (2.94, 5.88, 8.82, and 11.76 J/cm²). These spectra exhibit characteristic absorption bands with peak located at around 400 for Ag NPs which is corresponds to the SPR of Ag NPs [26, 27].



Figure 2: Optical properties of Ag NPs prepared by PLAL at fluence: (a) 2.94 J/cm², (b) 5.88 J/cm², (c) 8.82 J/cm², (d) 11.76 J/cm²



Figure 3: Absorbance of Ag NPs in water

In order to study the stability of plasmonic absorption with time, the absorbance of the Ag colloids was measured at different periods. As shown in Figure (4), with the passing of time, there was no clear change in peak position but the intensity of SPR band initially increases with time especially at long wavelengths. The constant position of absorbance peak indicates that the particles do not significantly aggregate or agglomerate. The stability of the colloidal depends, size, shape, liquid medium. Also, liquid medium in which the NPs are dissolved can affect the surface charge of NPs. Analogous surface charges create repulsive forces among the NPs and this type of forces keep the the NPs away from each other and this effect increases the stability of NPs colloidal. We have experimentally observed that Ag NPs have more stability in absorbance than Au NPs. Figure 5 shows the amount of the ablated material (AAM) for Ag NPs as a function of laser fluence. It is observed that the concentration of NPs increases with laser fluence. This has a good agreement with Figure 2, where the color of colloid becomes darker with increased of the particle concentration in the solution.

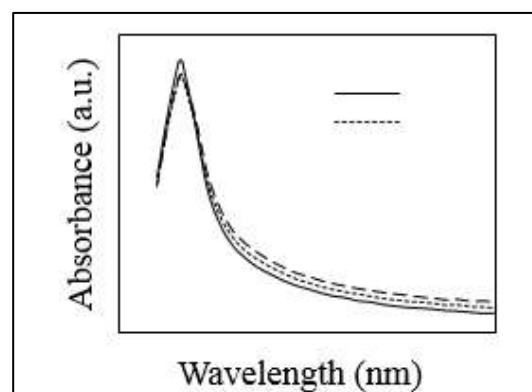


Figure.4: Plasmonic absorption of Ag NPs with time

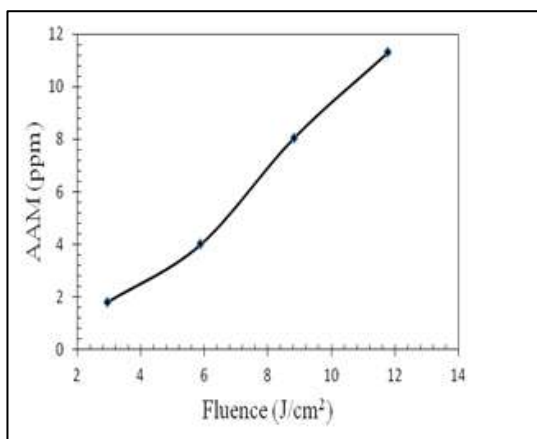


Figure 5: AAM for (a) Ag NPs prepared by PLAL

The reduction in particle size of Ag NPs can be attributed to the absorption of high energy, which excites Ag NPs in a solution. After absorption of photon energy, the extra energy is converted to internal modes inside the NPs. Each Ag NP can absorb more than one thousand photon and as a result, the NPs temperature increases significantly so that the NPs start to fragment into smaller NPs. In every pulse, the NPs are suffering from heating and cooling [28]. It was reported that the average particle size became smaller with increased pulse energy. This can be explained as follows: an increased laser power increases the temperature of NPs and a faster quenching rate leads to reduction of the NP size [29].

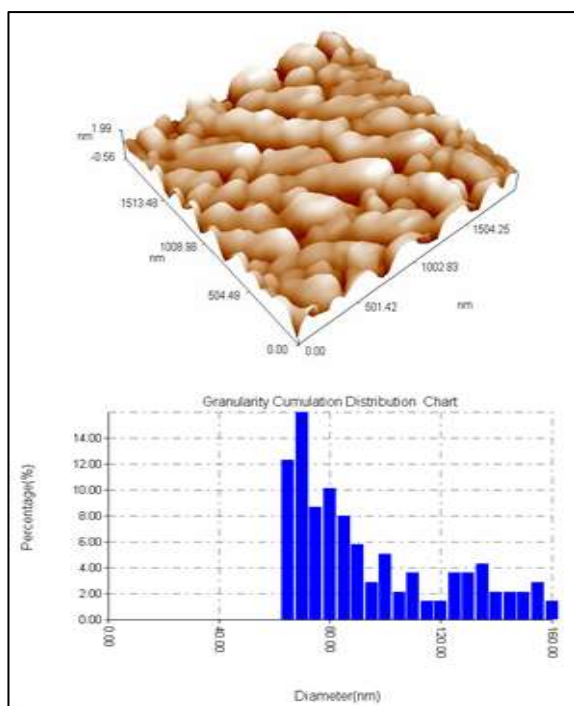


Figure 6: AFM image for Ag NPs prepared by PLAL at fluence 2.94 J/cm².

The size of Ag NPs decreases until they attain their critical size. It is observed that higher laser energies seem to excite more collisions between the vapor atoms/ions, this effect leads to coalesce rate in the ablated plume, and hence the NPs within the plume coagulate to form larger NPs [29,30].

Figure 7 shows the FTIR spectrum for silver NPs colloid. The spectrum was recorded the wave number of the incident light in the range (400-4000 cm⁻¹). The minimums in transmittance at 3278.8 cm⁻¹ and 1641 cm⁻¹ are corresponding the absorption bands of O-H stretching and H O H bending, respectively. The absorption band at 437.8 cm⁻¹ is due to Ag while the minimum point at 513 cm⁻¹ for Ag O is not appeared in this spectrum [31-33]. Figure 8 shows the I-V curves for Ag NPs for Si-solar cell before and after the incorporation of Ag NPs. An enhancement in I_{sc} can be ascribed to plasmonic effect of the Ag NPs, which have the ability to scatter more photons toward the silicon substrate compared with NPs-free solar cells. The best result are obtained when the particle size between 79 and 92 nm. These results are in good agreement with [34,35]. In fact, smaller NPs have smaller ratio of scattering-to- absorption cross-section, so smaller NPs scatter less light than larger NPs. Consequently, some absorption loss results from the existence of smaller NPs. The increases in J_{sc} and η are results from a little increase in FF following the drop casting of NPs. Figure 8 shows I-V characteristics of our silicon solar cell with Ag NPs prepared by PLAL at fluence 2.94 J/cm² and deposited onto the surface of silicon solar cells. For comparison, the I-V characteristics of the reference Si-solar cell without Ag NPs is also shown.

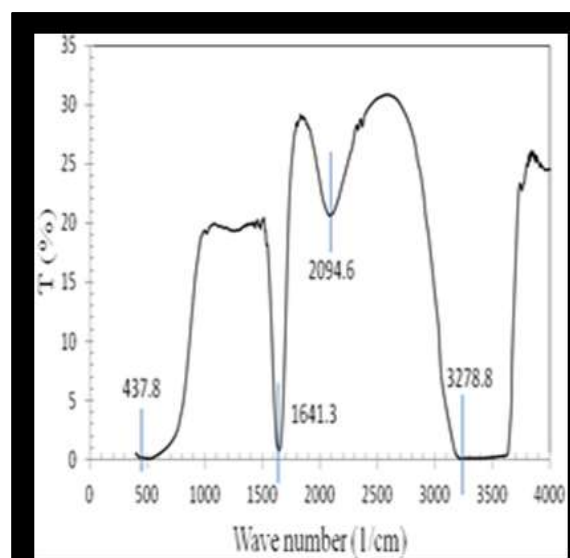


Figure 7: FTIR spectra for Ag NPs at 800 mJ.

Table 1: Si-solar cell parameters with different diameters of Ag NPs

Si-solar cell	Average Particle size (nm)	J_{sc} (mA/cm ²)	V_{oc} (V)	F.F	η	Enhancement of J_{sc}
Reference Si-solar cell	-	11.03	0.42	0.455	2.1	14%
Si-solar cell with AgNPs	92	12.62	0.43	0.465	2.4	
Reference Si-solar cell	-	7.79	0.42	0.506	1.7	12.8%
Si-solar cell with AgNPs	87	8.79	0.42	0.533	1.8	
Reference SI- Si-solar cell	-	15.36	0.47	0.466	3.5	6%
Si-solar cell with Ag NPs	83	16.29	0.47	0.485	3.57	

The detailed factors of the solar cells with and without Ag NPs are summarized in Table 1. As shown in Figure 9, the Responsivity of Si-solar cell with Ag NPs is higher than that for the reference solar cell (without Ag NPs). The figure is an indication that the Si-solar cell with Ag NPs has better absorbance of the solar spectrum in the visible and near IR regions.

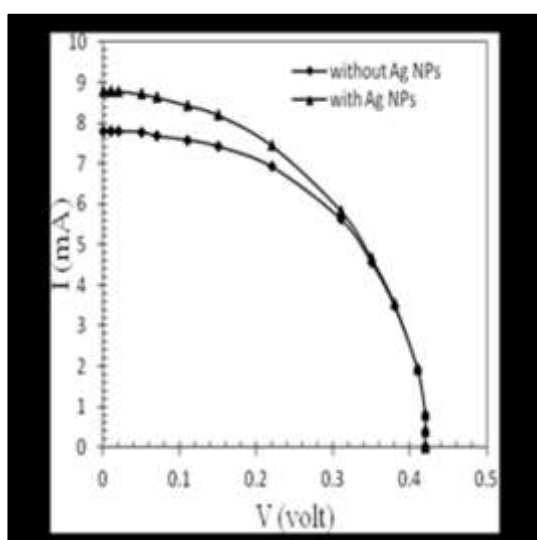


Figure 8: I-V characteristic for solar cell with silver NPs prepared by PLAL with fluence 2.94 J/cm²

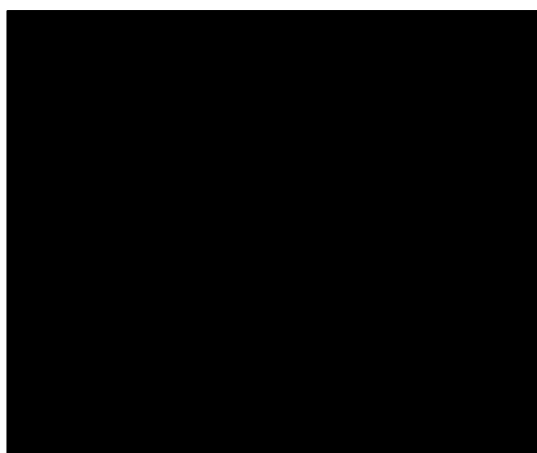


Figure 9: Responsivity for solar cell with Ag NPs at laser fluence 2.94 J/cm²

4. Conclusions

PLAL technique has been proved a rapid and simple technique to prepare pure Ag NPs. The size of the NPs could be controlled by choosing the proper laser fluence and the liquid medium. The deposition of Ag NPs on the front side of silicon solar cells can provide better absorbance in the visible region and hence enhances the conversion efficiency of silicon solar cell by virtue of surface plasmon resonance.

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