Materials Research Express

PAPER

Enhancing the efficiency of dye-sensitized solar cell by increasing the light trapping and decreasing the electron-hole recombination rate due to Ag@TiO₂ core-shell photoanode structure

Milad Fallah 1*, Iraj Maleki 1,2,3, Mohammad-Reza Zamani-Meymian 1* and Yaser Abdi 1*
1 Department of Physics, Iran University of Science and Technology, Iran
2 Department of Physics, University of Tehran, Iran
3 These authors contributed equally to the work.

E-mail: r_zamani@iust.ac.ir

Keywords: PCE of DSSC, light trapping, electron-hole recombination, Ag@TiO₂ core-shell, surface plasmonic resonance

Abstract

In this research, efficiency enhancement of dye-sensitized solar cell (DSSC) with Ag doped TiO₂ core-shell (C–S) as plasmonic photoanode structure, abbreviated as Ag@TiO₂, was investigated using Sol-Gel- Dr Blade method. Different amount of Ag in two different thick of photoanode were applied to enhance the light absorption for high-performance DSSCs. The localized surface plasmonic resonance (LSPR) effect of Ag@TiO₂ showed an improvement in light trapping and power conversion efficiency (PCE) of developed DSSCs. Conforming to the conclusions under AM 1.5 spectrum, the prepared plasmonic solar cells exhibited 21.9% and 41.46% increase in PCE for 13 μm and 8.4 μm thick of photoanode, respectively.

1. Introduction

Crystalline silicon SCs, representing about 90% of the world productions are known as the first generation SCs. However, researchers showed the computational PCE of silicon SCs would be restricted to 37% [1–4]. Inexpensive, scalability for mass-production, and light-weight flexible thin film modules like CdTe, CdSe, IGO, CIGS and amorphous silicon (a-Si) are among the most popular second generation SCs. Nonetheless, related devices have lower efficiency than the first generation due to their crystallinity destruction. Though thin film SCs are developing rapidly with efficiency rating as high as 22% for CIGS, nature-lovers have criticized this type of SCs due to hazardous and toxic elements [5–9]. Highly efficient, non-toxic and low-cost nanocrystal multijunction SCs represent the third class of SCs, maintaining the economical and environmental advantages of thin film deposition techniques. Nanocrystal or nanoporous materials including dye-sensitized-, quantum dot sensitized-, perovskite-, copper zinc tin sulfide (CZTS)- and organic SCs can be placed in this class [10–13]. Although oxide semiconductors within SCs have recently shown improved stability under irradiation, they cannot effectively absorb visible light because of their large band gap, leading to the photo-sensitizer concept [14, 15]. In 1991, Grätzel and his coworkers could significantly increase the optical absorption of SCs using mesoporous nanostructured electrodes [16–18]. Schemes 1 and 2 illustrate the mechanism as well as the charge transport mechanism of a typical DSSC.

Since 1991, considerable works have been done on DSSCs to improve the device efficiency. So far, the highest PCE that has been achieved on ruthenium-based DSSCs is over 14% but further challenges for increasing the efficiency as well as enhancing the durability and reducing the production costs are still the subjects ahead. That is why the DSCCs are still not manufactured in commercial scales. However, the main developments of DSSCs have been focused on improvement of following issues: (a) photoelectrode, (b) photosensitizers, (c) electrolyte and (d) counter electrode [19–25]. One of the key factors for increasing the efficiency of DSSCs is optimizing the light absorption. In 2011, Qi et al used Ag@TiO₂ C–S nanostructure within DSSC and showed that the advanced LSPs effect results in optical absorption enhancement and increases the PCE due to a strong localized electric field [26]. In 2014, Chang et al illustrated that Ag@TiO₂ C–S can form a porous structure with further surface area of photoanode as well as more dye adsorption and better penetration of electrolyte [27]. Also, Dong et al demonstrated that Ag nanowire@TiO₂ C–S can significantly accelerate the electron transport...
and reduce the charge recombination in DSSC [28]. In 2015, Chandrasekhar et al represented more generation of photoelectrons by enhancing the wavelength absorption region based on the role of reduced graphene oxide and plasmonic Ag@TiO2 C–S nanocubes on DSSC [29]. In 2017, Nbelayim et al found the influence of Ag@TiO2 C–S on fermi level modification of TiO2 photoanode of DSSC [30]. In 2018, Ibrayev et al understood the reduction in series resistance ($R_{ser}$) by creating of Ag@TiO2 C–S structures in DSSC [31]. Moreover, Nbelayim et al investigated the effects of multi-sized and -shaped Ag@TiO2 C–S on the efficiency of DSSC [32].

In this research, the influences of LSPR of Ag@TiO2 C–S structure on the PCE of prepared DSSC were studied. Ag-TiO2 photoanode in DSSCs has already been investigated and published in several literature, however, as the major novelty of this work, the plasmonic resonance effects in different percentage by weight (wt%) of Ag NPs have been investigated on performance of assembled DSSCs. Moreover, for the principle of reproducibility, two different thicknesses of titanium paste as a part of photoanode were fabricated and investigated.

2. Experimental

2.1. Materials

The precursors were prepared using absolute ethanol as solvent; acetic acid as dispersing agent; deionized (DI) water; distilled water; and absolute acetone; all were supplied by the Merck Co. Polyethylene glycol (PEG 35000)
as surfactant; titanium isopropoxide (TPO, 97%); titanium tetrachloride (TiCl₄, >99%); polyvinylpyrrolidone (PVP-25, mol. wt. ~25000); ethylene glycol (99.8%); polyacrylic acid solution (PAA, mol wt. ~90,000, 25 wt% in H₂O); ammonia solution (25–30 wt% in H₂O); and tetrabutylammonium hydroxide (TBAOH, 20 wt% in H₂O); all were purchased by the Sigma-Aldrich Co. Commercial fluorene doped tin oxide (FTO, 8 Ω/□) glass was purchased by Solaronix Co; chloroplatinic acid solution (6 wt% in H₂O); scotch tape and surlyn thermal adhesive; all were used from the Solaronix Co. The N719-dye was gained from GreatCell Solar Co. The liquid electrolyte based on (I⁻/I₃⁻) redox couple electrolyte was achieved from the Sharif solar Co, and silver nitrate (AgNO₃, >90%) powder was synthesized at school of metallurgy and materials engineering of IUST.

2.2. Analysis

A solar simulator was used to simulate the sun light fabricated by a set of xenon lamps and light-emitting diodes (LEDs) fabricated at nanophysics lab of Tehran University. Surface morphology was obtained by Scanning Electronic Microscope (SEM, HITACHI 4160). Images of microstructures was achieved by Transmission Electron Microscope (TEM, PHILIPS CM30). Spectroelectrochemistry was obtained by UV−vis spectrometer (Avantes-DH-S-BAL). A potentiostat (Palmsense4) was used for electrical and electrochemical measurements. The thickness of layers was gained by Dektak surface profilometer.

2.3. Synthesis of TiO₂ NPs paste

For this purpose, 21 ml DI water as well as 1.3 ml acetic acid were slowly stirred in a container (labeled as A) for 5 min via a magnetic stir–bar mixer, accompanied by adding 1 ml titanium isopropoxide solution under vigorous stirring in order to prevent sedimentation. The resulted solution was stirred at room temperature under middle stirring speed for 6 h, followed by placing the container A in a dark environment for 24 h to form the TiO₂ NPs. To preparation of the TiO₂ white paste, polyethylene glycol (10 wt%, PEG 35000) which was stirred for 1 h in another container added into container A. The final solution was stirred under middle stirring speed and heated for 6 h, simultaneously, by heating steps of 50 °C for 1 h each step. Finally, a white paste of TiO₂ NPs paste was obtained.

2.4. Synthesis of Ag NPs

In order to preparation of Ag NPs, 0.5 g of polyvinylpyrrolidone (PVP) was added to 25 ml ethylene glycol and the solution was stirred by a magnetic stir–bar mixer, followed by a sonication process using an ultrasonic bath at room temperature for 30 min afterwards, 0.1 mmol of silver nitrate was added by drop-wise addition to the solution. Silver nitrate can be agglomerated when exposure to light due to its high reactivity under light [33], so the solution was kept in dark and heated at 120 °C for 1 h with stirring slowly. The formation of Ag NPs was expected after this and a centrifuge technique was used to collect the prepared Ag NPs helping acetone and ethanol. Since ethanol is a polar solvent, metal NPs can be well dispersed within it [34]. The synthesized Ag NPs were added to a solution consists of 2 ml ammonia 4% in ethanol, and 18 ml ethanol, followed by vigorous stirring and sonication for 30 min this solution was used for C–S structuring.

2.5. Synthesis of Ag@TiO₂ core-shell

To preparation of Ag@TiO₂ C–S, 2 g of PAA was added to a solvent containing 1 ml distilled water and 8 ml ethanol. The final solution was stirred at room temperature for 1 h. Then, 0.2 ml of this solution was added to 10 ml solution of 0.05 mmol Ag NPs in ethanol. The resulted solution was stirred for 4 h and sonicated at room temperature for 30 min finally, a mixture of 1 ml ethanol and 6 μl TPO was added to the resulted solution and were stirred vigorously in the dark environment for 12 h. With this, the shell of TiO₂ NPs in a thickness of less than 5 nm placed on Ag NPs.

2.6. TiO₂ paste coating, annealing and sensitization processes

The substrates were first cut at 1 cm × 2 cm and cleaned according to the following steps: (a) pre-rinse with soap and DI water for 10 min in an ultrasonic bath; (b) rinse with DI water; (c) washing with 0.1 M HCl in ethanol for 10 min in ultrasonic bath; (d) rinse with DI water; (e) washing with acetone for 10 min in ultrasonic bath; (f) rinse with distilled water; and (g) washing with ethanol for 10 min in ultrasonic bath. A solution of 2 M TiCl₄ was made by 38 ml distilled water and 12 ml TiCl₄ and a more diluted solution with a concentration of 40 mM was then prepared from the resulted solution. The substrates were placed within the 40 mM solution and heated to 70 °C for 30 min. By this, a compact layer of TiO₂ was formed on the substrate. The reason for this process was to increase the porous adhesion of TiO₂ layer on the FTO and to reduce the e-h recombination of porous TiO₂ and electrolyte [35]. An area of 0.25 cm² of prepared substrate was selected via covering the rest of the substrate by the scotch tape. A thin layer of porous TiO₂ paste was then coated on the substrate using the Dr Blade process.
In this research, the thickness of 8.4 μm of TiO2 paste was used and for retesting the results, the thickness of 13 μm was also prepared. Scheme 3 shows the annealing process which was performed using temperature steps over time. The layers were annealed from the ambient temperature up to 500 °C at ambient pressure. To dye loading, the annealed photoanode was placed in a solution including 0.4 mM N719 powder dyes and absolute ethanol as solvent at 80 °C for 24 h.

2.7. Preparation of cathode and sealing process
To assemble the cathode, a hole was drilled on purchased FTO in order to electrolyte injection, followed by cleaning process that mentioned earlier in section 2.6. Then, a drop of 0.6 mM chloroplatinic acid solution was poured onto the FTO to cover its surface. For thermal treatment, the prepared FTO was annealed at 450 °C for 15 min.

Surlyn thermal adhesive was used as the sealing spacer. According to Scheme 4, after cutting in the middle of the surlyn polymer at 0.49 cm², the prepared surlyn was sandwiched between photoanode and cathode and the set was held under pressing of a clamp. This set was placed inside the oven at 110 °C for 90 s. the heat treatment caused the surlyn to melt and seal the SC. Then the electrolyte was injected within the device by the prepared hole space. Eventually, the hole was also sealed by the surlyn polymer. Scheme 4 illustrates the assembling process and figure 1 shows a typical sample of prepared DSSC.

3. Results and discussion

3.1. Morphological properties
The LSPs effect can be so impressive once the size of NPs is smaller than the wavelength of the incident light, so the size of TiO2 NPs in DSSCs has a significant effect on PCE [26]. Figure 2 shows the morphology of (A) TiO2, (B & C) Ag, and (D) Ag@TiO2 C–S NPs in which the smaller size of NPs than the wavelength has been proved. Figure 2(A) indicates the porous TiO2 NPs with mean particle size of about 25 nm with smooth and uniform surface as well as spherical shape without impressive agglomeration. Also, excessive granular porosity in Ag@TiO2 C–S NPs can offer high surface area, resulting in more dye adsorption. Moreover, smaller NPs of TiO2 leads to smaller pores that can cause an undesirable condition for electrolyte ion exchange rate [36].

Figures 2(B) and (C) illustrate the Ag NPs before implying the TiO2 shell with 0.25 g and 0.5 g of PVP, respectively. As can be seen the average grain size of Ag NPs is decreasing from 130 nm to 20 nm arises from higher amount of PVP. This can be attributed to the role of large PVP molecules as a surfactant and stabilizer of
metal colloids that prevent the excessive growth of Ag NPs by developing higher nucleation rate and creating a gap between Ag ions which intercept agglomeration. But low amount of PVP can cause agglomeration due to incomplete coverage of Ag NPs. It can be clearly shown from the figures 2(B) and (C) that the higher amount of PVP increases the distance between Ag NPs and results in reducing of aggregation and size of NPs [37, 38].

Figure 2(D) presents the SEM image of powder Ag@TiO2 C–S NPs with 0.5 g of PVP. Ag@TiO2 C–S NPs can be well dispersed in polar solvents such as ethanol. Therefore, the adhesion of NPs which is observed in the figure with 40 nm in size can be due to removal of ethanol for obtaining powder NPs. As it is difficult to distinguish between core and shell in figure 2(D), a TEM image is used in figure 3.

Figure 3 shows the TEM image of Ag@TiO2 C–S structure. For better recognition, the sharper images were also added in figure 3. According to the figure, it seems that the Ag core is surrounded by TiO2 shell. The individual spherical Ag NP core of about 40 nm mean diameter surrounded by amorphous TiO2 shell of about 5 nm thick. The dominant spherical morphology of Ag@TiO2 C–S NPs is suitable for LSPs effects in DSSC [26, 33]. Also, the completed covering of Ag core by TiO2 shell can protect the core metal from corrosion by electrolyte and aggregation that can form larger particles during the annealing process. In general, by combining the local surface plasmon resonance (LSPR) effects of Ag and capability of TiO2 in absorption of ultraviolet (UV) wavelength, Ag@TiO2 C–S NPs can extend the photoelectric reaction in DSSC [27].

3.2. Optical Properties
The optical response of Ag@TiO2 C–S NPs was studied and showed that the LSPR arising from Ag@TiO2 C–S NPs can affect the optical absorption within the DSSC. It is well known that the TiO2 NPs absorb the UV spectrum in a high level. On the other hand, LSPR effect can help in absorption of broader wavelength of light because the resonance of free electrons of Ag can be coupled with lower resonance frequency of incident light, leading to absorption of light in higher wavelength. Although the amount of loaded dye is constant in all samples, the localized electric field in around and on the surface of C–S structure can increase the probability of light trapping inside the cell based on a dipole in accordance to the interaction between amplified electric field of C–S structure and energy levels of dye molecules. Also, increase in optical path length within the photoanode due to scattering by larger Ag@TiO2 NPs can increase the opportunity of light to be trapped inside the DSSC.
Although the amount of loaded dye is constant in all samples, the mentioned electromagnetic interactions and light trapping condition are expected to improve the optical properties such as absorption spectrum inside the cell. This expectation can be reinforced by improved photovoltaic properties as well as figure 4 in which absorption spectrum of dye 719 with TiO₂ is presented which is comparable with absorption spectrum of Ag@TiO₂ C–S NPs. However, further tests on light absorption or exact amount of adsorbed dyes should be considered in future.

As it was expected, the TiO₂ NPs absorbed the UV spectrum in a high level due to its indirect and wide bandgap [40]. The redshifted UV-Vis absorption spectrum of Ag@TiO₂ C–S NPs with improved visible light absorption compared to Ag and TiO₂ NPs can be assigned to the LSPR effect [41]. Moreover, the clear plasmon peak for Ag nanoparticles at 403 nm shifted into 424 nm in Ag@TiO₂ C–S NPs that can be attributed to the TiO₂ amorphous shell with higher dielectric constant than that of PVP [26]. Further analysis by the IPCE test can lead to more specific results [42–44].

3.3. Photovoltaic Properties

DSSCs with and without Ag@TiO₂ C–S photoanode structure were made to investigate the influences of LSPR on photovoltaic properties, and two different amounts of Ag within TiO₂ paste were studied to explore the principle of reproducibility. Due to using Dr Blade’s technique, the thickness of photoanode depends upon the number of times it is done. Dye adsorption can increase in larger thickness of photoanode because of more adsorption sites, resulting in higher collection rate of electrons. However, thicker porous TiO₂ increases the distance of electron-transportation towards the FTO that can enhance the recombination probability of electrons with holes of I₃⁻ on the TiO₂ surface. Also, increase in thickness of photoanode can increase the possibility of cracking within the TiO₂ layer during annealing. Moreover, thicker TiO₂ is less transparent and prevents the light to penetrate and reach the bottom of the photoanode, easily, leading to reduction in
photoelectrons \([27, 45]\). So, to study the test-retest reliability, two different thicknesses of TiO\(_2\) paste corresponding to 8.4 and 13 \(\mu\)m have been investigated.

Figures 5 and 6 show the J-V curves of different DSSCs with various doping level of Ag from 0 to 1.0 wt% in 8.4 and 13 \(\mu\)m of thick, respectively. Ag NPs indicated the significant effect on \(J_{sc}\) and \(V_{oc}\) of the plasmon-enhanced photoanodes over the non-plasmonic ones. As it is illustrated, the \(J_{sc}\) is rising in both thicknesses of photoanode by increasing the amount of Ag from 0 to 0.6 wt%, and is decreasing in 1.0 wt% Ag content.

Table 1 demonstrates the \(J_{sc}\) for the prepared samples with 0 and 0.6 wt% Ag amount in dissimilar thick of photoanode. According to the table 1 and figures 5 and 6, for 8.4 \(\mu\)m of thick, the increase of \(J_{sc}\) from 9.01 mA cm\(^{-2}\) for non-plasmonic photoanode to 11.95 mA cm\(^{-2}\) in presence of 0.6 wt% Ag, followed by a reduction to 10.54 mA cm\(^{-2}\) for 1.0 wt% Ag were seen. Also, in relation to the sample with 13 \(\mu\)m thick of TiO\(_2\) paste, it can be seen that the \(J_{sc}\) is increasing from 15.36 mA cm\(^{-2}\) to 18.70 mA cm\(^{-2}\) for non-plasmonic photoanode and with 0.6 wt% Ag, respectively, followed by 15.74 mA cm\(^{-2}\) for 1.0 wt% Ag.

Increase in \(J_{sc}\) in a DSSC can be related to three main areas as enhancement of dye adsorption, efficient light trapping and more rapid charge transport \([46]\). As mentioned previously in section 3.1, Ag doping can increase the surface area of porous TiO\(_2\) NPs. The increased surface area as well as bipolar interaction formed between dyes and the C–S structure due to LSPR can result in more dye adsorption which stated in section 3.2. Also, increase in the light absorption due to LSPR effect and the increased optical path length would lead to higher light harvesting. Moreover, the electron-sink effect which captures and accumulates the exited electrons by Ag NPs and reduces the charge recombination can improve the electron transport towards the FTO \([30]\). These reasons can be ascribed to increment in \(J_{sc}\) in 0 to 0.6 wt% of Ag doping for both thicknesses of photoanodes.
However, Jsc declined with 1.0 wt% Ag NPs that can be assigned to the increased electron trapping states of metal cores, leading to electron-hole recombination probability [47]. The better condition for recombination can delay the movement of photogenerated electrons through the TiO2 due to increasing in interfacial resistance. It seems like that the trapping states exist in all samples but they can only be the dominant phenomenon in 1.0 wt% of Ag doping, resulting in higher photoelectron trapping over photoelectron generation rate in this case [48]. In thicker photoanode, the higher Jsc can be attributed to the positive effects of more possible dye adsorption and extra optical path length. Also, the further distance of electron transport which increase the recombination probability does not seem to be able to overcome on positive effects of higher thickness [49]. These positive effects of thickness are the reason of higher efficiency in 13 μm thick of photoanode without Ag than that of 8.4 μm thick with 0.6 wt% of Ag. Moreover, table 1 indicates the Voc changes for 0 and 0.6 wt% of Ag loaded within the photoanode with 13 μm thick that achieved higher Jsc than the sample with 8.4 μm thick of photoanode. It is well known that the Ag has higher fermi level than the TiO2 and the Ag@TiO2 C–S structure can create a plasmonic-modified photoanode. The plasmonic-photoanode materials coupling (Ag and TiO2) leads to an upward shift in the provided quasi fermi level of TiO2 towards more negative potentials [30]. The upward shift in quasi fermi level can be assigned to some factors such as a) the Ag and TiO2 fermi-level-coupling that may induce shallow traps, b) extra electron absorption due to more possible dye adsorption rate, c) electron-sink effect of Ag cores that causes electron accumulation, and d) maybe Moss–Burstein effect which is a result of more generated electrons due to higher level of metal doping in TiO2. The Voc can be described as the difference between the quasi fermi level of free electrons of TiO2 and the level of redox potential of the electrolyte. Therefore, Voc can be changed by a) band edge movement in TiO2, b) adjustment of the potential of the redox couple, and c) variation in recombination rate of injected electrons [32, 50–52]. So, as described in table 1 and figure 6, increase in Voc in presence of Ag@TiO2 C–S with optimal values of 0.76 and 0.75 V for 1.0 and 0.6 wt% Ag, respectively, can be attributed to the upward quasi fermi level shift and resistance of electrons against recombination due to better condition in electron transport.

Furthermore, the PCE of assembled DSSCs under AM 1.5 spectrum with 8.4 and 13 μm of TiO2 paste and 0 and 0.6 wt% of Ag can be seen in table 1. It is obvious that the LSPR effects of Ag can be effective for improvement in PCE of the prepared devices [53]. The best PCE was obtained 5.8% and 8.9% for 0.6 wt% of Ag with 8.4 and 13 μm of TiO2 paste, respectively, which were 41.46% and 21.9% higher as compared with that of the samples without Ag doping with PCE of 4.1% and 7.3% for 8.4 and 13 μm of TiO2 paste, respectively. The reasons for the improvement were argued previously which were related to the effects of Ag and LSPR on Jsc and Voc.

Table 1. Photovoltaic parameters of prepared DSSCs without Ag and with 0.6 wt% Ag in 8.4 and 13 μm thick of photoanodes.

| Thickness (μm) of TiO2 paste | Doping Level (wt%) of Ag | Jsc (mA cm⁻²) | Voc (V) | FF (%) | η (%) |
|-----------------------------|--------------------------|--------------|--------|--------|-------|
| 8.4 without                | 9.01                      | 0.70         | 65     | 4.10   |
| 8.4 0.6                    | 11.95                     | 0.73         | 66     | 5.80   |
| 13 without                 | 15.36                     | 0.71         | 67     | 7.30   |
| 13 0.6                     | 18.70                     | 0.75         | 64     | 8.90   |

Figure 6. J-V curves of assembled DSSC in different Ag amounts with 13 μm thick of photoanode.
The electron lifetime versus voltage curves are shown in figure 7 by using the following equation.

\[
\tau = \frac{k_B T}{e} \left( \frac{dV_{oc}}{dt} \right)^{-1}
\]

where \( k_B \) is the Boltzmann constant, \( T \) is the absolute temperature, \( e \) is the elementary charge, and \( t \) is the elapsed time. Increased electron lifetime usually is related to the reduced charge losses which is attributed to the internal recombination of the cell and dark condition in which the test is carried out. It can be seen that in the entire \( V_{oc} \) range, the lifetime for sample with 0.6 wt% Ag is longer than that of sample without Ag. Moreover, the constant electron lifetime at high \( V_{oc} \) for the sample without Ag can indicates the recombination via free electrons in the conduction band of TiO\(_2\) which is not visible in the other example. This can be ascribed to the lower charge recombination and carrier losses for the sample with 0.6 wt% Ag as compared to the sample without Ag [54–57].

4. Conclusion

In this work, plasmonic effects from Ag@TiO\(_2\) on performance of DSSC were investigated. For this purpose, various amounts of Ag (0 to 1 wt%) and two different thicknesses of photoanode (8.4 and 13 \( \mu \)m) were fabricated and the photovoltaic properties were analyzed. The best results were obtained when 0.6 wt% Ag was added to the TiO\(_2\) by which the best PCE of 8.9% was obtained for 13 \( \mu \)m thick and 5.8% for 8.4 \( \mu \)m thick of photoanode. These amounts showed a 21.9% and 41.46% increase in PCE in each case as compared to the reference cell without Ag. According to the results, it was shown that the LSPR effects resulted by Ag@TiO\(_2\) C–S structure, have an attractive influence on \( J_{sc} \) and \( V_{oc} \) of DSSCs because it can result in higher light trapping and better charge transporting condition.

Conflict of interest

The authors declare that they have no conflict of interest.

ORCID iDs

Milad Fallah https://orcid.org/0000-0003-0502-9710
Mohammad-Reza Zamani-Meymian https://orcid.org/0000-0002-8802-807X
Yaser Abdi https://orcid.org/0000-0002-7583-7687

References

[1] Lu X, Li Y, Lun S, Wang X, Gao J, Wang Y and Zhang Y 2019 High efficiency light trapping scheme used for ultrathin c-Si solar cells Sol. Energy Mater. Sol. Cells 196 57–64
[2] Kalaiselvi C R, Muthukumarasamy N, Velauthapillai D, Kang M and Senthil T S 2018 Importance of Halide Perovskites for next generation solar cells- a review Mater. Lett. 219 198–200
[3] Patni N, Sharma P and Pillai S G 2018 Newer approach of using alternatives to (Indium doped) metal electrodes, dyes and electrolytes in dye sensitized solar cell Mater. Res. Express 5 045509
[4] Liu J, Yao Y, Xiao S and Gu X 2018 Review of status developments of high-efficiency crystalline silicon solar cells J. Phys. D: Appl. Phys. 51 123001
Mater. Res. Express 7 (2020) 016409

M Fallah et al

[5] Matsui T, Sai H, Bidiville A, Hsu H-J and Matusbara K 2018 Progress and limitations of thin-film silicon solar cells Sol. Energy 170 486–98

[6] Powalla M, Paetel S, Harisoks D, Wuerz R, Kessler F, Lechner P, Wischmann W and Friedmeier T M 2017 Advances in cost-efficient thin-film photovoltaics based on Cu(In,Ga)Se2 Engineering 3 445–51

[7] Avrutin V, Izyumskaya N and Morkos H 2011 Semiconductor solar cells: recent progress in terrestrial applications Superlattices Microstruct. 49 357–64

[8] Jackson P, Wuerz R, Harisoks D, Lotter E, Witte W and Powalla M 2016 Effects of heavy alkali elements in Cu(In,Ga)Se2 solar cells with efficiencies up to 22.6% Phys. Status Solidi 10 353–6

[9] Hsieh T-M, Lue S-J, Ao J, Sun Y, Feng W-S and Chang I-L 2014 Characterizations of chemical bath-deposited zinc oxysulphide films and the effects of their annealing on copper-indium-gallium-selenide solar cell efficiency J. Power Sources 246 443–8

[10] Andrews J and Jelley N 2017 Energy Science Principles, Technologies, and Impacts (New York: Oxford) [https://doi.org/10.1007/ 9780470974704]

[11] Schmagera R, Gomarda G, Richards B S and Paetzold U W 2019 Nanophotonic perovskite layers for enhanced current generation and mitigation of lead in perovskite solar cells Sol. Energy Mater. Sol. Cells 192 65–71

[12] Comibeer G 2007 Third-generation photovoltaics Mater. Today 10 42–50

[13] Hrascey A 2018 Strategies to improve the performance of metal-free dye-sensitized solar cells Dyes Pigm. 149 707–18

[14] Luque A and Hegedus S 2011 Handbook of Photovoltaic Science and Engineering (Chichester: Wiley) [https://doi.org/10.1002/ 9780470977470]

[15] Abodurin T, Boyo A, Obafemi O and Adedayo T 2015 Characterization of dye sensitized cells using natural dye from oil bean leaf (pentaclethra macrophylla): the effect of Dye pH on the photovoltaic parameters Mater. Sci. Appl. 6 646–55

[16] Shah S H, Baharan N N S, Yusuf S N F and Arif A K 2019 Efficiency enhancement of dye sensitized solar cells (DSSCs) using copper nanopowder (CuNW) in TiO2 as photoanode IOP Conf. Ser. Mater. Sci. Eng. 515 012002

[17] Ghayour R, Keshavarz A, Soltani Rad M N and Mashreghi A 2018 Enhancement of photovoltaic performance of dye-sensitized solar cells based on TiO2-graphene quantum dots photoanode Mater. Res. Express 6 035205

[18] O’Regan B and Grätzel M 1991 A low-cost, high-efficiency solar cell based on dye-sensitized colloidal TiO2 films Nature 353 737–40

[19] Fallah M, Zamani-Meymian M R, Rahimi R and Rabbani M 2014 Effect of annealing treatment on electrical and optical properties of Nb doped TiO2 thin films as a TCO prepared by sol–gel spin coating method Appl. Surf. Sci. 316 156–62

[20] Robinson K, Kumara G R A, Kumara R J G L R, Jayaweera E N and Rajapakse R M G 2018 SnO2 nanoparticles on the performance of plasmonic dye-sensitized solar cells ACS Nano 12 10563–3

[21] Dong H, Wu Z, Lu F, Gao Y, El-Shafei A, Jiao B, Ning S and Hou X 2014 Optics nanomaterials and nanotechnology: prospective applications of advanced nanomaterials and nanotechnology in renewable energy technologies Optics Express 22 650304

[22] Nbelayim P, Kawamura G, Abdel-Galeil M M, Tan W K, Wei X, Muto H and Matsuda A 2018 Effects of multi-sized and -shaped Nb doped TiO2 thin films of Au nanoparticles and PEDOT:PSS conjugated polymer Org. Electron. 63 159–62

[23] Ravivarma M, Kumar A K, Rajakumar P and Pandurangan A 2016 Interface chargetransfer studies and fabrication of high performance DSSC with ethylene cored unsymmetrical dendrimers as quasi electrolytes J. Mol. Liq. 265 717–26

[24] Shenouda S S, Yahia I S, Hoda S and Hafez F 2019 Yakuphanoglu, Facile and low-cost synthesis of PEDOT:PSS / FTO polymeric counter electrode for DSSC, photosem with negative capacitance phenomenon Mater. Res. Express 6 025205

[25] Nemala S S, Aneja K S, Bhargava P, Bohm H L M, Mallick S and Bohm S 2018 Novel high-pressure airless spray exhaust method for graphene nanoplatelets as a stable counter electrode in DSSC Electrochim. Acta 285 86–93

[26] Gong J, Sumathy K, Qiao Q and Zhou Z 2017 Review on dye-sensitized solar cells (DSSCs): Advanced techniques and research trends Renew. Sust. Energy Rev. 68 234–46

[27] Zhao F, Ma R and Jiang Y 2018 Strong efficiency improvement in dye-sensitized solar cells by novel multi-dimensional TiO2 photoelectrode Appl. Surf. Sci. 443 11–5

[28] Qi J, Dang X, Hammond P T and Belcher A M 2011 Highly efficient plasmonic-enhanced dye-sensitized solar cells through metal@oxide core–shell nanostucture ACS Nano 5 7108–16

[29] Chang H, Chen C-H, Kao M-J and Hsaio H-H 2014 Effect of core–shell Ag@TiO2 volume ratio on characteristics of TiO2-based DSSCs J. Nanomater. 2014 8

[30] Dong H, Wu Z, Lu F, Gao Y, El-Shafei A, Jiao B, Ning S and Hou X 2014 Optics–electronics highways: Plasmonic silver nanowires@TiO2 core–shell nanocomposites for enhanced dye-sensitized solar cells performance Nano Energy 10 181–91

[31] Chandrashekar P S, Chander N, Anjaneyulu O and Komarala V K 2015 Plasmonic effect of Ag@TiO2 nanoparticles on the performance of bio-inspired colloidal silver nanoparticles incorporated dye sensitized solar cells J. Nanomater. J. Mater. Chem. 239 139

[32] Babaahmadi V, Montazer M, Toliyat T and Ghanbarafsh M 2011 Photochemical reduction of silver nitrate to nano silver using stannous chloride, cit and daylight irradiation Nanomater. Appl. Prop. 1 183–90 [http://essuir.sumbdu.edu.ua/bitstream/ 123456789/20633/1/32.pdf]

[33] Bricha M and Mabrouk K E 2019 Effect of surfactants on the degree of dispersion of MWNTs in ethanol solvent Colloids. Surf. A Physicochem. Eng. Asp. 561 57–69

[34] Chang H-C, Twu M-J, Hsu C-Y, Hsu R-Q and Kuo C-G 2014 Improved performance for dye-sensitized solar cells using a compact TiO2 layer grown by sputtering J. Phys. Energy 2014 8

[35] Tricoli A, Wallerand A S and Righettini M 2012 Highly porous TiO2 films for dye sensitized solar cells J. Nanomater. J. Mater. Chem. 22 14252

[36] Jukić M, Svilben I, Žorić Z and Milardović S 2012 Effect of polyvinylpyrrolidone on the formation AgBr grains in gelatine media Crum. Chem. Acta 85 269–76

[37] Dang T M D, Le T T T, Fribourg- Blanc E and Dang M C 2012 Influence of surfactant on the preparation of silver nanoparticles by polyl method Adv. Nat. Sci.: Nano. Nanotechnol. 3 4

[38] Maruno S 2019 Surface plasmon spectroscopy of thin composite films of Au nanoparticles and PEDOT:PSS conjugated polymer Org. Electron. 64 154–7

[39] Fallah M, Zamani-Meymian M R, Rahimi R and Rabbani M 2018 Influence of two gradual steps of vacuum annealing on structural and opto-electronic characteristics of Nb-doped TiO2 transparent conducting oxide Superlattices Microstruct. 123 242–50

[40] Ramanarayanan R, Chokkireddi N, Pullanjiyot N, Meethal B N and Swaminathan S 2019 The deterministic role of resonance energy transfer in the bio-inspired colloidal silver nanoparticles incorporated dye sensitized solar cells Mater. Res. Bull. 114 28–36
[42] Ihara M, Kanno M and Inoue S 2010 Photoabsorption-enhanced dye-sensitized solar cell by using localized surface plasmon of silver nanoparticles modified with polymer Physica E 42 2867–71
[43] Hwanga H-J, Joos S-J, Patilb S A and Kim H-S 2017 Efficiency enhancement in dye-sensitized solar cells using the shape/size-dependent plasmonic nanocomposite photoanodes incorporating silver nanoplates Nanoscale 9 7960–9
[44] Neshat A and Safdari R 2019 Enhancement in dye-sensitized solar cells using surface plasmon resonance effects from colloidal core-shell Au@SiO2 nanoparticles ChemistrySelect 4 4995–5001
[45] Zhang H, Wang W, Liu H, Wang R, Chen Y and Wang Z 2014 Effects of TiO2 film thickness on photovoltaic properties of dye sensitized solar cell and its enhanced performance by graphene combination Mater. Res. Bull. 49 126–31
[46] Xu Y, Zhang H, Li X, Wu Q, Wang W, Li Z and Li J 2017 Investigation of the improved performance with ferrites in TiO2 dye-sensitized solar cell Appl. Surf. Sci. 424 245–50
[47] Chen M and He Y 2018 Plasmonic nanostructures for broadband solar absorption based on the intrinsic absorption of metals Sol. Energy Mater. Sol. Cells 188 156–63
[48] Pascoe A R, Bourgeois L, Duffy N W, Xiang W and Cheng Y-B 2013 Surface state recombination and passivation in nanocrystalline TiO2 dye-sensitized solar cells J. Phys. Chem. C 117 25118–26
[49] Wu X, Lu G and Wang L 2013 The effect of photoanode thickness on the performance of dye-sensitized solar cells containing TiO2 nanosheets with exposed reactive (001) facets J. Mater. Res. 28 475–9
[50] Sakthivel T, Ashok Kumar K, Ramanathan R, Senthilvelan J and Jagannathan K 2017 Silver doped TiO2 nano crystallites for dye-sensitized solar cell (DSSC) applications Mater. Res. Express 4 126310
[51] Ogunsolu O O, Wang J C and Hanson K 2017 Increasing the open-circuit voltage of dye-sensitized solar cells via metal-ion coordination Inorg. Chem. 56 11168–75
[52] Dong J, Jia J, Cao B and Wu J 2019 Spin-coated cobalt telluride counter electrodes for highly efficient dye-sensitized solar cells Mater. Res. Bull. 115 65–9
[53] Wang L et al 2018 Light absorption and efficiency enhancements for organic photovoltaic devices with Au@PSS core-shell tetrahedra Org. Electron. 61 96–103
[54] Ivanovska T, Saponjic Z, Radovic M, Ortolani L, Morandi V and Ruani G 2014 Improvement of dye solar cell efficiency by photoanode posttreatment Int. J. Photoenergy 2014 10
[55] Su T, Yang Y, Jiang Y, Shi Y, Fan R and Cao W 2016 Prolonged lifetime and retarded recombination in dye sensitized solar cells using hydrogenated fluorine doped TiO2 nanocrystals as a photoanode RSC Adv. 6 99251–9
[56] Giannouli M, Govatsi K, Syrrokostas G, Yannopoulos S N and Leftheriotis G 2018 Factors affecting the power conversion efficiency in ZnO DSSCs: nanowire vs. nanoparticles Materials 11 411
[57] Milan R, Selopal G S, Epifani M, Natile M M, Sberveglieri G, Vomiero A and Concina I 2015 ZnO@SnO2 engineered composite photoanodes for dye sensitized solar cells Sci. Rep. 5 14523