



A very simple flexible tandem dye-sensitized solar cell

Hussain Alessa¹ · K. G. U. Wijayantha²

Received: 2 January 2024 / Accepted: 12 February 2024 / Published online: 16 March 2024
© The Author(s) 2024

Abstract

Dye-sensitized solar cells (DSSCs) have been proposed as the most important third generation photovoltaic devices owing to their low fabrication cost, design flexibility, having low hazard to the environment and ease of construction. Tandem DSSCs (T-DSSC) were said to possess properties of its sensitized photoanode and sensitized photocathode in terms of the power conversion efficiency (PCE) parameters. With less studies on the fabrication of simple a flexible tandem DSSC, this work aims at filling this gap as well as showing the influence of one of the main factors that affect the performance of such a device. In this paper, TiO₂ and NiO layers were prepared by blading method, sensitized separately, then sandwiched together. The fabricated device produced short circuit current, open circuit voltage and power conversion efficiency of 0.138 mA.cm⁻², 0.942 V and 0.063%, respectively. This simple T-DSSC produced a high photovoltage and showed that the photocurrent produced by each photoelectrode should be identical. This match is to overcome the possible hump in the device performance.

Keywords Tandem Dye-sensitized solar cells · TiO₂ · NiO · Flexible photovoltaic

1 Introduction

It has been several decades since the pressure was put on the utilization of the available energy sources, as petroleum derivatives are the commonly known examples, for meeting the population growth as well as the economic advancement. Unfortunately, the usage of the non-renewable energy sources has negative impacts on the environment and the living organisms. Necessity is the mother of invention; this has attracted economists and policy makers for finding clean energy sources like photovoltaics [1–3]. The use of solar energy technology would benefit in producing photon-to-electron energy from the most abundant energy source; the sun, and this technology does not require intensive maintenance like other energy sources. The solar energy can be harvested in different ways to produce energy, like the conversion of the sun light into electricity or using this light for splitting water to produce green hydrogen [4, 5].

Dye sensitized solar cells (DSSCs), also known as Grätzel cells, were demonstrated in 1991 as a favourable low-cost solution to silicon solar cells. These cells were fabricated by using a large band gap semiconductor, TiO₂, which was sensitized with an organic light harvester; dyes. The energy levels of the solar cell's components must be well engineered, so that upon absorbing the light, electrons can be injected from the highest occupied molecular level (HOMO) to the lowest unoccupied molecular level (LUMO) of the dye, which then injected to the conduction band (CB) of the semiconductor, while the holes are sent to the electrolyte. The electrons flow through the external circuit to reduce the electrolyte which had been oxidized upon injecting electrons for re-generating the dye. Another path for making the DSSCs is by replacing TiO₂, n-type semiconductor, with a p-type one like NiO. The dyes in this case inject holes to the valence band (VB) of the semiconductor, which then diffuse to the cathode electrode [6]. Grätzel's invention encouraged scientists worldwide for advancing this type of solar cells, as it was predicted to be a promising way of finding an economically reasonable devices for harvesting solar energy. This is to compete the conventional photovoltaic (of the first two solar cells' generations) as DSSCs can be fabricated at lower cost and from eco-friendly materials. Additionally, the technology advancement has been going on fast, meeting the lifestyle trend when utilized in portable wireless electronic

✉ Hussain Alessa
hhessa@uqu.edu.sa

¹ Chemistry Department, Faculty of Science, Umm Al-Qura University, 21955 Makkah, Saudi Arabia

² Centre for Renewable and Low-Carbon Energy, Cranfield University, College Road, Cranfield, Bedfordshire MK43 0AL, UK

devices such as laptops, music players and mobile phones. Currently, these devices live on battery supply of energy [7].

The advantages of fabricating solar cells onto flexible conductive plastic substrates stem from a relatively low-cost manner allowing them to meet the industrial requirement for easy fabrication. On the other hand, there are some challenges when constructing thin films of semiconductors on flexible substrates. These stem from the temperature-restricted deposition methods. Most DSSCs have been fabricated on rigid substrates, like conductive glass, using binders and sintering at high temperatures to enhance the adhesion of the films onto the substrate. Unfortunately, the melting points of the plastic substrates (less than 180 °C for polyethylene naphthalate (PEN) and even lower for polyethylene terephthalate (PET)) prevent the usage of high temperatures [8]. Therefore, a mechanical compression seems to be a good method for enhancing the film-substrate adhesion as well as the inter-particle contact.

The first p-type DSSCs is accounted for Lindquist and co-workers; they constructed NiO-based DSSC in 1999, opening the door for a competition with the counterpart n-type DSSCs [9]. Sooner after that, the same group constructed the first tandem dye sensitized solar cell (T-DSSC) on glass substrates, in which TiO₂ was sensitized with cis-di(thiocyanato)-N,N-bis(2,2',-bipyridyl-4,4',-dicarboxylic acid)-ruthenium (II), N719 dye as the photoanode whereas erythrosine B-dyed NiO was the photocathode. It was noticed that the power conversion efficiency (PCE) of the T-DSSC was lower than TiO₂-DSSC. This observation was blamed to unmatched photocurrent from the involved two photoelectrodes. The photovoltage of the T-DSSC was the sum of the individual photoelectrodes when being constructed in a separate DSSC [10]. The fabrication of T-DSSCs, by attaching both photoanode and photocathode sensitized with relevant dyes, was said to be a way of enhancing the individual DSSCs type, cathodic or anodic. The strict requirement of fabricating T-DSSCs is that the establishment of current density matching of both photoelectrodes [10].

It should be mentioned that, as the solar cells can generate electricity from the sunlight during the daytime, this may hinder its capability to produce electricity comparable to the current conventional energy sources. One of the solutions to conquer this matter is to convert the sunlight into other fuels like oxygen and hydrogen. This conversion can be done by using photoelectrochemical cell (PEC) in a process known as photo-electrolysis, and the hydrogen can be conserved to be used in fuel cells to generate electricity. Moreover, the resulted hydrogen from splitting process can be used as fuel that is not harming the environment. The production of green hydrogen as a renewable source of energy would arise several advantages, such as relative high energy per weight unit, fuel for energy generation, mitigating the use of

carbon-based energy, lowering the danger of global warming [11]. The produced hydrogen would be used and utilized by chemical and petroleum industries. It is estimated that 78% of hydrogen came from natural gas reservoir and oil whereas only 4% came from water electrolysis.

There have been several materials used for water photodecomposition with different sorts of radiation [12, 13]. The use of oxide semiconductors in photochemical cells for solar-to-fuel cells was seen to offer lower fabrication cost and higher stability. The solar energy can be harnessed by the semiconductors that involved in the PEC cell [14–16].

The fabrication of tandem DSSC requires using two sensitized electrodes, at least, stacked together which can produced higher photovoltages compared to a single junction solar cell. TiO₂ and NiO were among photoelectrodes used in DSSC. Their use in water splitting requires higher stability of these semiconductors in aqueous solutions, have conduction bands (CB) and valence band (VB) positions that are suitable for the charge transfer, also has high transparency in the visible region [17, 18].

Indium tin oxide (ITO) exhibit many advantages that advanced its ability to be utilised in various scientific fields, in photovoltaics, sensors and water splitting [19–21]. These are related to its low fabrication cost, being optically transparent and having outstanding electrical conductivity [22]. ITO can be deposited onto plastic or glass substrates by different techniques, and its thermal stability was seen to increase with increasing the grain size [23]. TiO₂ has been the main candidate as a photoanode, used in many applications, due to its high surface area, oxidizing ability and positive CB potential, about – 100 mV against normal hydrogen electrode at pH=0, which is above the redox potential for splitting water. Pristine TiO₂ has a large band gap of around 3.2 eV which make it difficult to absorb the visible and infrared light parts of the solar radiation, which is one of its main drawbacks. Doping TiO₂ to narrow its band gap would overcome this problem and enhance its absorption [24, 25]. The morphology of TiO₂ can also be modified for better PEC water splitting [26–29].

In PEC cells, TiO₂ absorbs the solar energy creating holes and electrons, the holes on its surface would oxidize water to produce oxygen while electrons are transferred to the photocathode, like Pt or NiO, to reduce water and form hydrogen [30–32]. The photocatalytic efficiency of water splitting, and hydrogen production is badly affected by the charge recombination between the semiconductor and the used catalyst, therefore, the inhibition of back electron transfer is needed and can be done by using SnO₂/TiO₂ core-shell as an example [33].

ZnO and Fe₂O₃ are another n-type semiconductor used in PEC water splitting. The former has a band gap energy like TiO₂ and suffer from the same problem regarding its absorbance range of the solar spectrum. Hence it underwent

similar treatments of doping and surface improvement [34, 35]. Although, Fe_2O_3 has a narrower band gap, of 2.1 eV, which make it favourable for water splitting, it suffers from poor charge transportation. Doping to enhance its electrical conductivity were mandatory [36].

NiO has been the most p-type semiconductor utilized in DSSC and PEC. Its VB potential is 400 mV against NHE in phosphate buffer having pH=6.8. Sensitizers must have HOMO more positive than VB of NiO, this is to transfer the excited electrons from its VB to the dye if used for DSSC [37]. Usually, pristine NiO suffers from charge recombination, poor charge mobility and unfavourable charge transfer at the interfaces. This requires improving its properties by doping process or chemical modifying the sensitizers. These treatments would enhance its photoconversion ability and photocatalytic properties [38, 39].

In this study, a demonstration of an easy way to fabricate a T-DSSC, from all solution processable materials, on conductive plastic substrates is shown. A flexible T-DSSC is constructed using nanostructured TiO_2 and NiO which were sensitized separately by N719 and coumarin 343 dyes, respectively. The electrical characterization of the flexible T-DSSC is evaluated by using current–voltage characteristics; the J – V of flexible T-DSSC was compared with two references of DSSCs constructed from TiO_2 -DSSC and NiO-DSSC, individually. A schematic diagram of the cell's components is shown in Fig. 1.

The mechanism of T-DSSC takes all processes occurring in n-DSSC and p-DSSC into account. In n-DSSC, the sensitizer (the dye) is excited by the bombarding photons and excite photo-generated electrons from its highest occupied

molecular level (HOMO) to the lowest unoccupied molecular level (LUMO), then inject the electrons to the conduction band (CB) of the semiconductor, the electrons diffuse through the semiconductor layer to the transparent conducting oxide (TCO) electrode while the holes are sent to the counter electrode. Similar process occurs in p-DSSC, but the holes are injected upon the light excitation to valence band (VB) of the semiconductor while electrons are sent to reduce the electrolyte and reach the anode by diffusing process. An illustration of these processes is shown in Fig. 1.

2 Experimental methods

It should be noted that all the chemicals were used as received without further purification. Both the photoanode and the photocathode were constructed using simple method at low temperature.

2.1 The photoanode preparation

The TiO_2 thin layers were doctor bladed from ethanolic paste. The TiO_2 paste was prepared by placing 7 g of TiO_2 (P25 powder) into a ball milled jar, followed by 16 g of absolute ethanol, the mixture was ball milled for nearly 15 h at a rate of 230 r.p.m. The formed mixture was stored in a sealed glass container and kept in a fridge. A thin film of the paste was coated on ITO/PEN flexible substrates ($13 \Omega/\text{cm}^{-2}$, Pecell Technologies, Inc., Japan) by doctor blade method, this was done at the laboratory ambient conditions, followed by drying at room temperature for few minutes before being annealed at 150°C , then with compress treatment at 30 kN. The same conditions of coating and annealing were done two further times but at 30 and 0 kN, respectively. The TiO_2 electrodes were soaked in 1×10^{-4} M ethanolic N719 (ditetrabutyl-4,4'-dicarboxylate) dye (Solaronix SA) for 10 h.

2.2 The photocathode preparation

The NiO thin layers were doctor bladed from ethanolic paste. The NiO paste was prepared by placing 7 g of NiO powder into a ball milled jar, followed by 16 g of absolute ethanol, the mixture was ball milled for 15 h at a rate of 230 r.p.m. The formed mixture was stored in a sealed glass container and kept in a fridge. A thin film of NiO was doctor bladed onto ITO/PEN flexible substrates ($13 \Omega/\text{cm}^{-2}$, Pecell Technologies, Inc., Japan), this was done at the laboratory ambient conditions, followed by drying at room temperature for few minutes before being annealed at 150°C , then underwent compression treatment at 30 kN. The coating, annealing and compression were done two further times

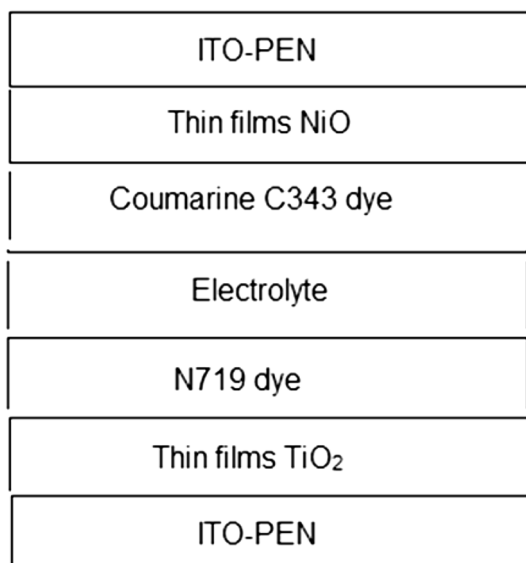


Fig. 1 The schematic diagram of the flexible Tandem DSSCs construction

but at 0 kN. The NiO electrodes were soaked in 1×10^{-4} M ethanolic coumarin 343 dye for 10 h.

2.3 The electrolyte

The electrolyte system consisted of a conventional iodide/triiodide based redox system; 5 ml acetonitrile, 5 ml 3-methoxypropionitrile, 0.4 M LiI (0.5354 g), 0.4 M Tetra butyl ammonium iodide (1.4775 g TBAI), 0.04 M I_2 (0.1015 g) and 0.3 M N-methyl benzimidazole (0.3965 g NMB).

2.4 n-type DSSCs

TiO_2 electrodes sensitised with N719 dye were rinsed with ethanol absolute to remove the excess dye molecules, then cleaned the surroundings around the active area with cotton buds. A sylurn tape was placed around the active area. Finally, Pt electrode, with a hole made in it, was placed on the active photoanode. The two electrodes were ironed for few seconds before the introduction of the electrolyte through the hole with the vacuum system.

2.5 p-type DSSCs

NiO electrodes sensitised with coumarin 343 dye were rinsed with ethanol absolute to remove the excess dye molecules, then cleaned the surroundings around the active area with cotton buds. A sylurn tape was placed around the active area. Finally, Pt electrode, with a hole made in it, was placed onto the active photocathode. The two electrodes were ironed for few seconds before the introduction of the electrolyte through the hole with the vacuum system.

2.6 Tandem DSSCs

In this configuration, TiO_2 and NiO electrodes were sensitised using different dyes. TiO_2 was used as the photoanode whereas NiO was the photocathode. The injection of the electrolyte was through a hole made in the photoanode. TiO_2 electrodes sensitised with N719 dye were rinsed with ethanol absolute to remove the excess dye molecules, then cleaned the surroundings around the active area with cotton buds. A sylurn tape was placed around the active area. NiO electrodes sensitised with coumarin 343 dye were rinsed with ethanol absolute to remove the excess dye molecules, then cleaned the surroundings around the active area with cotton buds. The two electrodes were ironed for few seconds before the introduction of the electrolyte through the hole with the vacuum system.

2.7 Treatment with $Mg(OH)_2$

0.01 M $Mg(NO_3)_2 \cdot 6H_2O$ (Sigma Aldrich) aqueous solution was prepared and used for electrodepositing $Mg(OH)_2$ layer onto TiO_2 layer for 120 s, before soaking the photoanode in the N719 dye for 10 h. Followed by sandwiching the sensitised photoanode with NiO sensitised photocathode and the conventional iodide electrolyte was used for facilitating the charge movement.

3 Results and discussion

Before discussing the results, it would be appropriate to explain the working mechanism of T-DSSC.

According to Fig. 2, the dye is excited upon the bombard-ing photons, injecting electrons to the conduction band of TiO_2 which diffuse to the working electrode, while the holes are sent to the electrolyte. The open circuit voltage, V_{oc} , of the tandem cell is determined by the energy difference between the CB of TiO_2 and VB of NiO.

It is known that in order to obtain a good T-DSSC, the photocurrent produced by both photoelectrodes should be matched [10]. This could be done by optimising both the thickness of the semiconductor layers and the amount of the dye adsorbed onto the photoelectrodes. The performance of T-DSSC and the reference cells (individual n-type and p-type DSSCs) was evaluated by examining the current density–voltage (J – V) measurements. The key parameters for evaluating the solar cells, performance, open-circuit voltage (V_{oc}), short-circuit current (J_{sc}), fill factor (FF) and the efficiency (η) are shown in Tables 1 and 2.

At the first stage of this work, the J – V measurements showed a promising working process with V_{oc} of 0.832 V and J_{sc} of 0.701 mA/cm^2 , as is shown in Fig. 3, however, there is a deform in the J – V curve indicating a high series resistance, which causes low FF, this could be due to the incapability of the NiO photocathode to produce a photocurrent density identical to the photoanode counterpart.

It was noticed that the TiO_2 paste was concentrated, thus giving thicker films allowing high amount of the dye molecules to be adsorbed. This would result in producing higher photocurrent than the NiO photoelectrode can produce. To overcome this problem, the TiO_2 paste was diluted in ethanol, 1:7 mL (v/v). As a result, the TiO_2 -DSSC gave a photocurrent identical to NiO-DSSC after this treatment. Figure 4a–c show this effect whereas Table 1 summarized the findings. The NiO DSSC produced 156 mV, TiO_2 DSSC produced 759 mV whereas the T-DSSC produced 942 mV. The photocurrent produced by each solar cell was identical, indicating strong match between the photocurrent produced by each single DSSC. It is assumed that the connection between the TiO_2 nanoparticles occurred during the drying

Fig. 2 schematic diagram showing the working principle of T-DSSCs

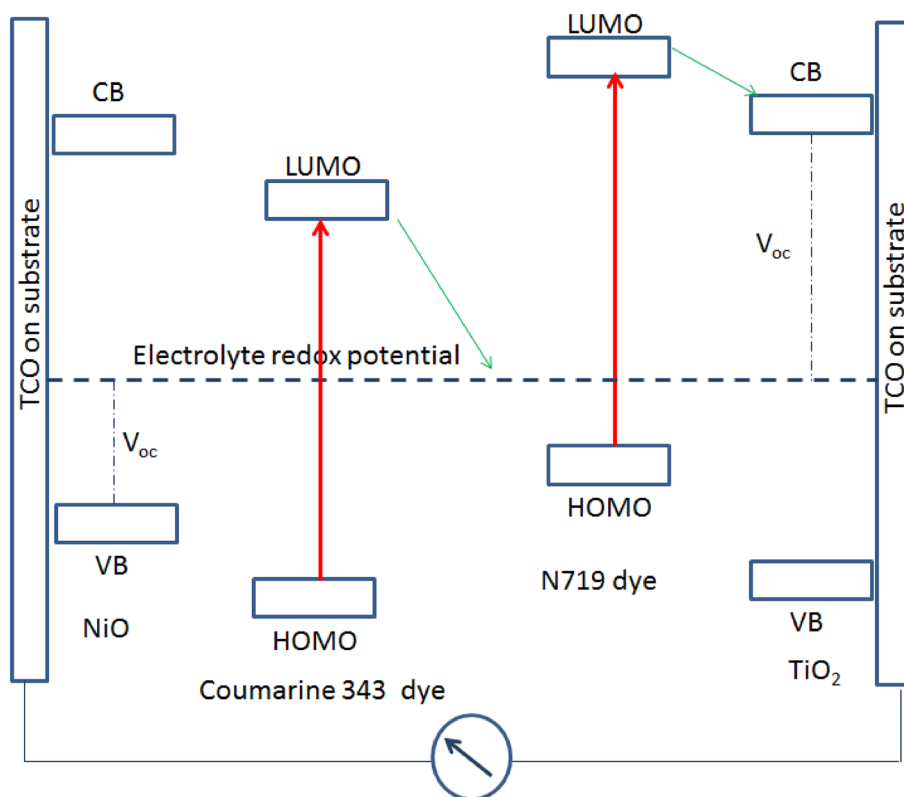


Table 1 The open circuit voltage (V_{oc}) and short circuit current (J_{sc}) of individually constructed photoelectrodes of tandem DSSC as well as the total T-DSSC

Solar cell	V_{oc} (mV)	J_{sc} (mA.cm ⁻²)	Figures
TiO ₂ -based	759	0.132	4a
NiO-based	156	0.133	4b
T-DSSC	942	0.138	4c

Table 2 Summary of the measured key parameters of all DSSCs shown in this work

Solar cell	V_{oc} (mV)	J_{sc} (mA.cm ⁻²)	FF	η (%)	Figures
Initial flexible T-DSSC	832	0.701	0.12	0.002	3
Flexible n-DSSC	759	0.132	0.51	0.05	4a
Flexible p-DSSC	156	0.133	0.39	0.008	4b
Flexible T-DSSC	942	0.138	0.49	0.063	4c
Flexible T-DSSC treated with Mg(OH) ₂	964	0.0774	0.42	0.031	6c

process of the paste, this resulted from removing water of the hydrogen bonded network of OH-covered titania particles.

The dilution treatment showed an improved performance, compare Figs. 3 and 4c. It could be seen that the dilution

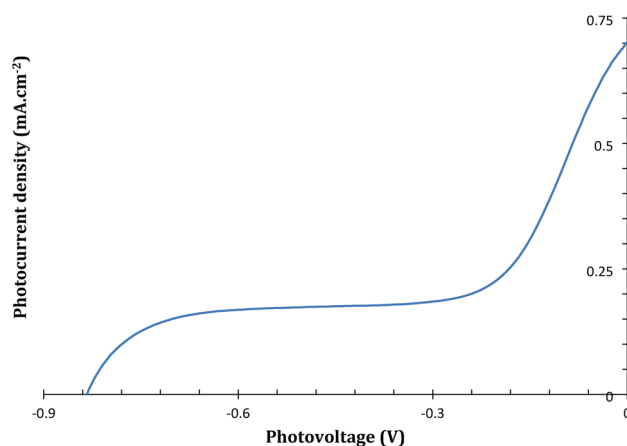


Fig. 3 Photocurrent density–voltage curve under illumination for T-DSSC constructed from non-diluted TiO₂ paste and NiO paste

resulted in identical photocurrents produced by individual DSSCs, as is shown in Fig. 4. This is proven by the transmittance measurements, as shown in Fig. 5, which confirmed the outstanding capability of the semiconductors' thin films to transmit light in the visible light and infrared light regions of the solar spectrum, this means high percentages of the light reaching the sensitizers. High amounts of photons would bombard the dyes and forcing them to inject the charge carriers onto the respected semiconductors.

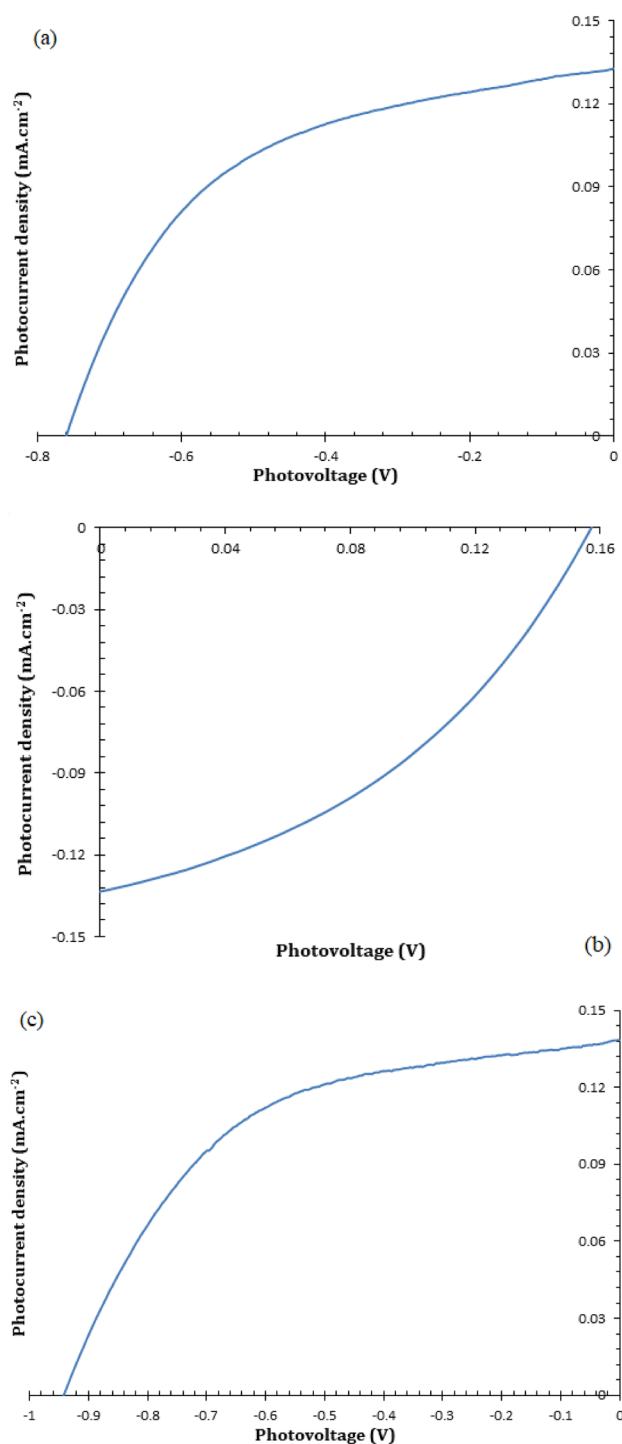


Fig. 4 Photocurrent density–voltage curve of **a** TiO₂-based DSSC, NiO-based DSSC (**b**) and **c** flexible T-DSSC

It was seen that the open circuit voltage V_{oc} of the flexible T-DSSC is 942 mV (Fig. 4c), 759 mV for n-DSSC (Fig. 4a) while 156 mV for p-DSSC (Fig. 4b), which means the V_{oc} of the reference cells are adding together when constructing flexible T-DSSC. The short circuit current J_{sc} of both

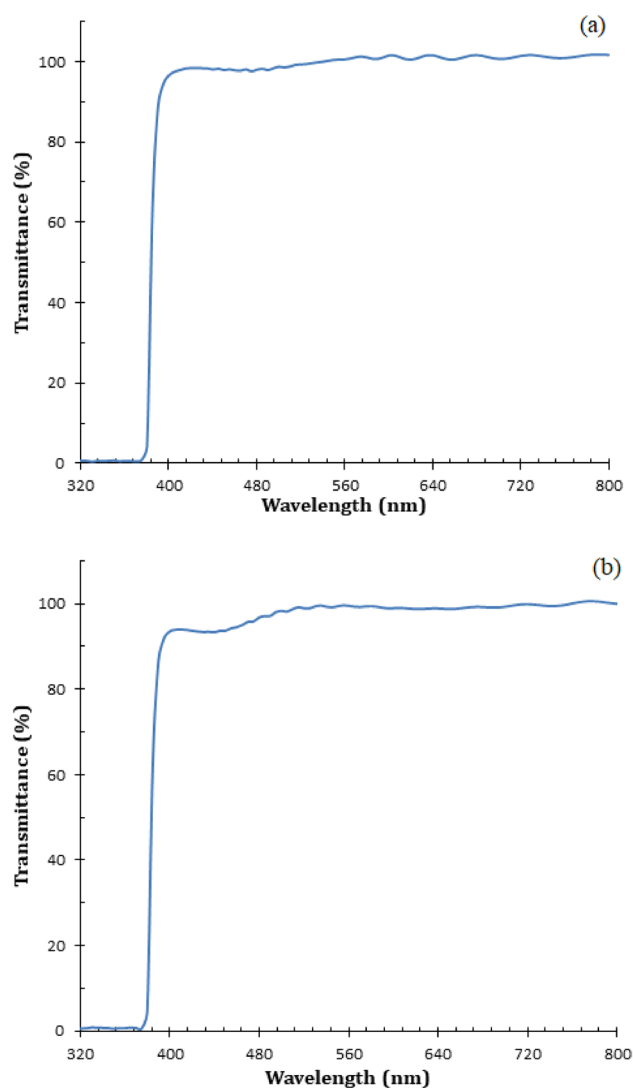


Fig. 5 **a** Transmittance measurement of the TiO₂ electrode and **b** the NiO electrode

n-DSSC and p-DSSC are matched when utilised in the construction of the flexible T-DSSC; 0.138 mA cm^{-2} . Furthermore, a layer of $\text{Mg}(\text{OH})_2$ was electrodeposited onto TiO₂ photoanode for 120 s followed by soaking the photoanode in the N719 dye for 10 h before constructing the T-DSSC. This treatment showed improved V_{oc} by 2.34% to 964 mV, however the J_{sc} decreased to $0.0774 \text{ mA cm}^{-2}$ as in Fig. 6. It should be noted that the illumination was done from both sides of T-DSSC as well as from each side individually. The efficiency parameters are shown in Tables 2 and 3.

Although, the treatment of the photoanode with $\text{Mg}(\text{OH})_2$ before constructing the T-DSSC resulted in an increase in the V_{oc} , a drop by nearly 50% of the photocurrent is observed when compared without the treatment. This would be explained by looking at the illumination from individual side of the tandem cell (Fig. 6a and b). In other words, the

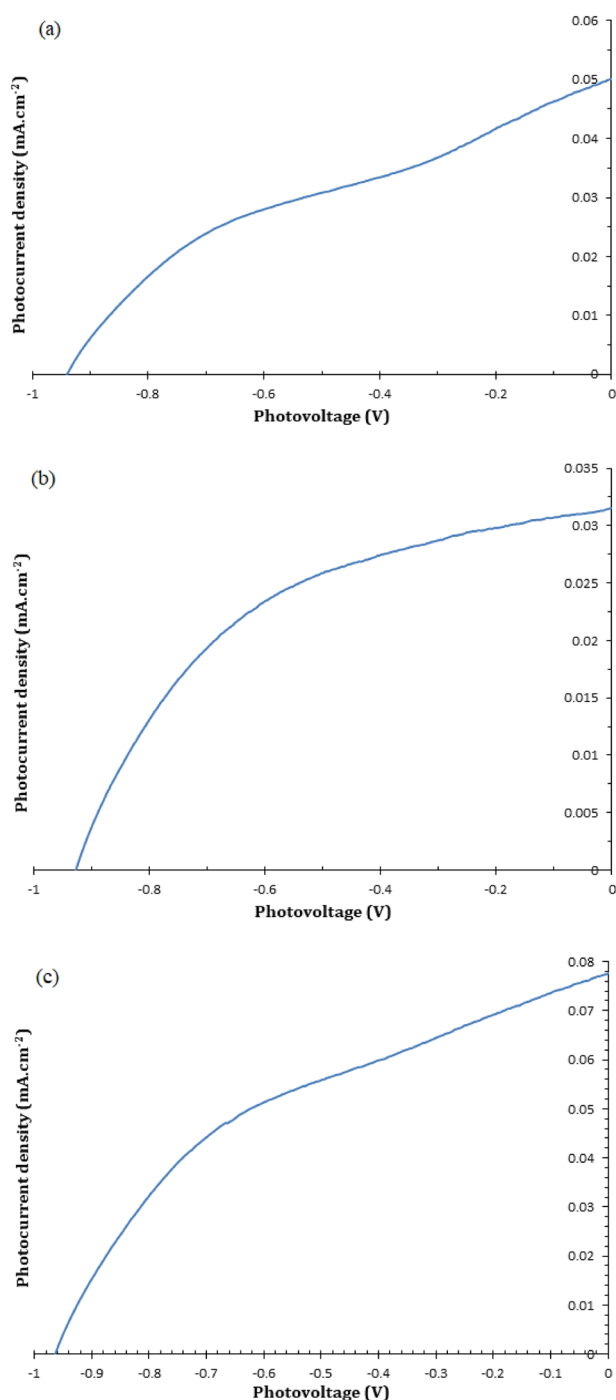


Fig. 6 J–V curve of flexible T-DSSC illuminated from **a** TiO₂ side, **b** NiO side and **c** both sides

Mg(OH)₂ could have shifted the conduction band of the photoanode, which increased the V_{oc} produced by the photoanode, thus enhancing the tandem cell V_{oc} . The literature suffers from the lower amounts of publications regarding the fabrication of these flexible devices. Table 4 shows a list of the literature compared with the current work. The majority of the literature focused on the fabrication of such

Table 3 The open circuit voltage (V_{oc}) and short circuit current (J_{sc}) of the T-DSSC treated with Mg(OH)₂

Illumination side of T-DSSC	V_{oc} (mV)	J_{sc} (mA.cm ⁻²)	Figures
TiO ₂ -side	938	0.0499	6a
NiO-side	924	0.0315	6b
Both sides	964	0.0774	6c

The illumination is from each side and from both sides

device onto rigid substrates. This was performed by using fluorine-doped tin oxide (FTO) or indium-doped tin oxide (ITO) coated onto glass substrates as the platform of the devices.

As a matter of truth, these devices are fabricated in a simple manner showing their capabilities in converting the sun light to electricity. However, as they were fabricated onto flexible substrates, they would not stand high temperatures as they would deform and start melting around 235 °C, beside that these devices were fabricated without binders. Taking the sintering restriction and the neglection of the binders into account, poor interconnection of the semiconductors particles is the result which would increase the sheet resistance that is usually above 60 Ω/sq [44], which was observed in this work. It was reported that the fabrication of semiconductors from free-binder pastes would lead to formation of large cavities among the particles. This may influence the connection between semiconductors' particles and the electron transfer pathway [45]. Overall, this work showed that the ability of fabricating simple tandem DSSCs that can produce high voltages with no need for binders neither for high temperature sintering. This work is believed to be possibly used during water splitting by PEC cells if its performance is improved, such as by further doping the semiconductors or using perovskite absorbers like CH₃NH₃PbI₃ or its derivatives.

4 Conclusion

A flexible T-DSSC was constructed from binder-free TiO₂ and NiO pastes, and were sensitised with N719 and coumarin dyes, respectively onto ITO/PEN substrates by using doctor blading technique. It was proved that flexible T-DSSC is able to deliver a V_{oc} much higher than a single semiconductor DSSC. The illumination from both sides of the T-DSSC delivered better results than from single side of the cell. The performance of the fabricated T-DSSC was reasonable as it was made on flexible substrates restricting the heat treatment for better inter-particle connectivity. This tandem solar cell would be good candidate for supplying energy to PEC cells during water splitting process.

Table 4 The comparison of the results in this work with the literature

Solar cell	V _{oc} (mV)	η (%)	References
Flexible T-DSSC (ITO-PEN/TiO ₂ /N719 dye/(I ⁻ /I ₃ ⁻) electrolyte/coumarin dye/NiO/ITO-PEN)	942	0.063	This work
Flexible T-DSSC treated with Mg(OH) ₂	964	0.031	
NR	920	NR	[40]
T-DSSC on FTO glass substrate., TiO ₂ as a photoanode, NiO as a photocathode and Co ^{+2/+3} electrolyte	910	NR	[41]
T-DSSC on glass substrate (FTO /TiO ₂ /N719 dye/(I ⁻ /I ₃ ⁻) electrolyte/NiO/FTO)	940	0.98	[42]
T-DSSC on glass substrate (FTO /TiO ₂ /SQ dye/(Co ^{+2/+3}) electrolyte/P1 dye/NiO/FTO)	680	1.91	[43]

Author contributions H. Alessa conducted the work, analyzed the outcomes, wrote the manuscript and revised it. KGU Wijayantha initiated the work and analyzed the findings.

Funding No fund was received regarding this manuscript.

Data availability The data will be made available on reasonable request.

Declarations

Conflict of interest The authors declare no conflict of interest.

Open Access This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if changes were made. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit <http://creativecommons.org/licenses/by/4.0/>.

References

- Coiante D, Barra L (1992) Can photovoltaics become an effective energy option? *Sol Energy Mater Sol Cells* 27:79–89. [https://doi.org/10.1016/0927-0248\(92\)90045-Q](https://doi.org/10.1016/0927-0248(92)90045-Q)
- International Energy Agency (IEA). Available at: <https://www.iea.org/reports/global-energy-review-2021>. Accessed 25 Dec 2023
- Takagi K, Magaino S, Saito H, Aoki T, Aoki D (2013) Measurements and evaluation of dye-sensitized solar cell performance. *J Photochem Photobiol C Photochem Rev* 14:1–12. <https://doi.org/10.1016/j.jphotochemrev.2012.08.003>
- Ali I, Imanova GT, Mbianda XY, Alharbi OM (2022) Role of the radiations in water splitting for hydrogen generation. *Sustain Energy Technol Assess* 51:101926. <https://doi.org/10.1016/j.seta.2021.101926>
- Ali I, Imanova G, Alharbi OML et al (2023) Recent updates in direct radiation water-splitting methods of hydrogen production. *J Umm Al-Qura Univ Appl Sci*. <https://doi.org/10.1007/s43994-023-00115-9>
- O'Regan B, Grätzel M (1991) A low-cost, high-efficiency solar cell based on dye-sensitized colloidal TiO₂ films. *Nature* 353:737–740. <https://doi.org/10.1038/353737a0>
- Yamaguchi T, Tobe N, Matsumoto D, Arakawa H (2007) Highly efficient plastic substrate dye-sensitized solar cells using a compression method for preparation of TiO₂ photoelectrodes. *Chem Commun* 45:4767–4769. <https://doi.org/10.1039/B709911H>
- Hine PJ, Astruc A, Ward IM (2004) Hot compaction of polyethylene naphthalate. *J Appl Polym* 93:796–802. <https://doi.org/10.1002/app.20517>
- He J, Lindström H, Hagfeldt A, Lindquist SE (1999) Dye-sensitized nanostructured p-type nickel oxide film as a photocathode for a solar cell. *J Phys Chem* 103:8940–8943. <https://doi.org/10.1021/jp991681r>
- He J, Lindström H, Hagfeldt A, Lindquist SE (2000) Dye-sensitized nanostructured tandem cell-first demonstrated cell with a dye-sensitized photocathode. *Sol Energy Mater Sol Cells* 62:265–273
- Basheer AA, Ali I (2019) Water photo splitting for green hydrogen energy by green nanoparticles. *Int J Hydrog Energy* 44:11564–11572. <https://doi.org/10.1016/j.ijhydene.2019.03.040>
- Imanova GT, Agayev TN, Jabarov SH (2021) Investigation of structural and optical properties of zirconia dioxide nanoparticles by radiation and thermal methods. *Mod Phys Lett B* 35:2150050. <https://doi.org/10.1142/S0217984921500500>
- Ansari MZ, Singh S, Khare N (2019) Visible light active CZTS sensitized CdS/TiO₂ tandem photoanode for highly efficient photoelectrochemical hydrogen generation. *Sol Energy* 181:37–42. <https://doi.org/10.1016/j.solener.2019.01.067>
- Wang Y, Vogel A, Sachs M et al (2019) Current understanding and challenges of solar-driven hydrogen generation using polymeric photocatalysts. *Nat Energy* 4:746–760. <https://doi.org/10.1038/s41560-019-0456-5>
- Arakawa H, Shiraishi C, Tatemoto M et al (2007) Solar hydrogen production by tandem cell system composed of metal oxide semiconductor film photoelectrode and dye-sensitized solar cell. *Solar Hydrog Nanotechnol II* 6650:32–41. <https://doi.org/10.1117/12.773366>
- Yin X, Liu Q, Yang Y et al (2019) An efficient tandem photoelectrochemical cell composed of FeOOH/TiO₂/BiVO₄ and Cu₂O for self-driven solar water splitting. *Int J Hydrog Energy* 44:594–604. <https://doi.org/10.1016/j.ijhydene.2018.11.032>
- Puga AV (2016) Photocatalytic production of hydrogen from biomass-derived feedstocks. *Coord Chem Revs* 315:1–66. <https://doi.org/10.1016/j.ccr.2015.12.009>
- Xu P, McCool NS, Mallouk TE (2017) Water splitting dye-sensitized solar cells. *Nano Today* 14:42–58. <https://doi.org/10.1016/j.nantod.2017.04.009>
- Kim JH, Seok HJ, Seo HJ et al (2018) Flexible ITO films with atomically flat surfaces for high performance flexible perovskite solar cells. *Nanoscale* 10:20587–20598. <https://doi.org/10.1039/C8NR06586A>
- Zheng X, Qiao X, Luo F, Wan B, Zhang C (2021) Low-cost high-performance NO₂ sensor based on nanoporous indium tin oxide

- (ITO) film. *Sens Actuators, B Chem* 346:130440. <https://doi.org/10.1016/j.snb.2021.130440>
21. Rabia M, Shaban M, Jibali BM, Abdelkhaliek AA (2020) Effect of annealing temperature on the photoactivity of ITO/VO₂ (M)/Au film electrodes for water splitting. *J Nanosci Nanotechnol* 20:4120–4130. <https://doi.org/10.1166/jnn.2020.17681>
 22. Althagafi II, Ahmed SA, El-Said WA (2019) Fabrication of gold/graphene nanostructures modified ITO electrode as highly sensitive electrochemical detection of Aflatoxin B1. *PLoS ONE* 14:e0210652
 23. Nishimoto N, Yamada Y, Ohnishi Y, Imawaka N, Yoshino K (2013) Effect of temperature on the electrical properties of ITO in a TiO₂/ITO film. *Phys Status Solidi* 210:589–593. <https://doi.org/10.1002/pssa.201228325>
 24. Chen X, Mao SS (2007) Titanium dioxide nanomaterials: synthesis, properties, modifications, and applications. *Chem Revs* 107:2891–2959. <https://doi.org/10.1021/cr0500535>
 25. Khan SUM, Al-Shahry M, Ingler WB Jr (2002) Efficient photochemical water splitting by a chemically modified n-TiO₂. *Science* 297:2243–2245. <https://doi.org/10.1126/science.1075035>
 26. Paulose M, Shankar K, Yoriya S et al (2006) Enhanced photocleavage of water using titania nanotube arrays. *J Phys Chem B* 110:16179–16184. <https://doi.org/10.1021/jp064020k>
 27. Rani S, Roy SC, Paulose M et al (2010) Synthesis and applications of electrochemically self-assembled titania nanotube arrays. *Phys Chem Chem Phys* 12:2780–2800. <https://doi.org/10.1039/B924125F>
 28. Demir E, Inam R, Ozkan SA et al (2014) Electrochemical behavior of tadalafil on TiO₂ nanoparticles–MWCNT composite paste electrode and its determination in pharmaceutical dosage forms and human serum samples using adsorptive stripping square wave voltammetry. *J Solid State Electrochem* 18:2709–2720. <https://doi.org/10.1007/s10008-014-2529-5>
 29. Abdulwahed JAM, Alshehri K (2023) The optical characteristics and co-evaporation processing of CuInGaSe₂ thin film. *J Umm Al-Qura Univ Appl Sci*. <https://doi.org/10.1007/s43994-023-00073-2>
 30. Brennaman MK, Dillon RJ, Alibabaei L et al (2016) Finding the way to solar fuels with dye-sensitized photoelectrosynthesis cells. *J Am Chem Soc* 138:13085. <https://doi.org/10.1021/jacs.6b06466>
 31. Fujishima A, Honda K (1972) Electrochemical photolysis of water at a semiconductor electrode. *Nature* 238:37–38. <https://doi.org/10.1038/238037a0>
 32. Chen X, Shen S, Guo L, Mao SS (2010) Semiconductor-based photocatalytic hydrogen generation. *Chem Revs* 110:6503–6570. <https://doi.org/10.1021/cr1001645>
 33. Wee KR, Sherman BD, Brennaman MK et al (2016) An aqueous, organic dye derivatized SnO₂/TiO₂ core/shell photoanode. *J Mater Chem A* 4:2969. <https://doi.org/10.1039/C5TA06678F>
 34. Shet S, Ahn KS, Nuggehalli R, Yan YF, Turner J, Al-Jassim M (2011) Phase separation in Ga and N co-incorporated ZnO films and its effects on photo-response in photoelectrochemical water splitting. *Thin Solid Films* 519:5983–5987. <https://doi.org/10.1016/j.tsf.2011.03.050>
 35. Yousefi M, Amiri M, Azimirad R, Moshfegh AZ (2011) Enhanced photoelectrochemical activity of Ce doped ZnO nanocomposite thin films under visible light. *J Electroanal Chem* 661:106–112. <https://doi.org/10.1016/j.jelechem.2011.07.022>
 36. Kronawitter CX, Mao SS, Antoun BR (2011) Doped, porous iron oxide films and their optical functions and anodic photocurrents for solar water splitting. *Appl Phys Lett* 98:092108. <https://doi.org/10.1063/1.3552711>
 37. Zhang S, Ye H, Hua J, Tian H (2019) Recent advances in dye-sensitized photoelectrochemical cells for water splitting. *Energy-Chem* 1:100015. <https://doi.org/10.1016/j.enchem.2019.100015>
 38. Kamire RJ, Majewski MB, Hoffeditz WL et al (2017) Photodriven hydrogen evolution by molecular catalysts using Al₂O₃-protected perylene-3, 4-dicarboximide on NiO electrodes. *Chem Sci* 8:541–549. <https://doi.org/10.1039/C6SC02477G>
 39. Materna KL, Beiler AM, Thapper A, Ott S, Tian H, Hammarström L (2020) Understanding the performance of NiO photocathodes with alkyl-derivatized cobalt catalysts and a push–pull dye. *ACS Appl Mater Interfaces* 12:31372–31381. <https://doi.org/10.1021/acsami.0c05228>
 40. Nakasa A, Usami H, Sumikura S et al (2005) A high voltage dye-sensitized solar cell using a nanoporous NiO photocathode. *Chem Lett* 34(4):500–501. <https://doi.org/10.1246/cl.2005.500>
 41. Gibson EA, Smeigh AL, Pleux LL et al (2009) A p-type NiO-based dye-sensitized solar cell with an open-circuit voltage of 0.35 V. *Angew Chem* 121(24):4466. <https://doi.org/10.1002/anie.200900423>
 42. Qian J, Jiang KJ, Huang JH et al (2012) A selenium-based cathode for a high-voltage tandem photoelectrochemical solar cell. *Angew Chem* 51(41):10351–10354. <https://doi.org/10.1002/anie.201204108>
 43. Ho P, Thogiti S, Cheruku R, Ahn KS, Kim JH (2018) Enhanced efficiency via blocking layers at photocathode interfaces in cobalt-mediated tandem dye-sensitized solar cells. *Sol Energy* 161:9–16. <https://doi.org/10.1016/j.solener.2017.12.035>
 44. Dawo C, Chaturvedi H (2023) Recent advances in the development of flexible dye-sensitized solar cells: fabrication, challenges and applications-a review. *Flex Print Electron* 8:013001. <https://doi.org/10.1088/2058-8585/acb660>
 45. Muliani L, Hidayat J, Anggraini PN (2016) Performance analysis of flexible DSSC with binder addition. *AIP Conf Proc*. <https://doi.org/10.1063/1.4945504>

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.



DSPACE

<https://dspace.org/>

A very simple flexible tandem dye-sensitized solar cell

Alessa, Hussain; Wijyantha, Upul K. G.

2024-12-01

Springer

<https://doi.org/10.1007/s43994-024-00136-y>

Alessa H, Wijyantha KGU. (2024) A very simple flexible tandem dye-sensitized solar cell. Journal of Umm Al-Qura University for Applied Sciences, Volume 10, Issue 4, December 2024, pp. 698-706