RESEARCH ARTICLE



Strategic graphene integration in multilayer photoanodes for enhanced quasi-solid-state dye-sensitized solar cells and performance under variable irradiance

T. M. W. J. Bandara¹ · S. M. S. Gunathilake¹ · G. G. D. M. G. Gamachchi¹ · B. M. K. Pemasiri¹ · L. Ajith DeSilva² · M. A. K. L. Dissanayake³ · G. R. A. Kumara³

Received: 27 April 2024 / Accepted: 13 September 2024 © The Author(s), under exclusive licence to Springer Nature B.V. 2024

Abstract

Graphene is a potential candidate material to boost efficiency in solar cells. The performance of multilayer TiO₂ photoanodebased quasi-solid-state dye-sensitized solar cells (DSSCs) is improved by strategically integrating graphene into the appropriate layer of the photoanode. For this purpose, graphene was synthesized from vein graphite, received directly from the mine site, providing a cost-effective, feasible, and new approach to enhance DSSC efficiency. Raman and XRD spectra confirm the successful exfoliation of graphite, forming graphene. Graphene integration into layers was analyzed using SEM images. The cells were constructed using photosensitized spin-coated TiO₂ multilayer photoanode, Pt counter electrode, and binary salt gel polymer electrolyte. Appreciable performance improvement was observed when graphene was added to the fourth layer of the photoanode. The quasi-solid-state DSSC without graphene demonstrated 5.50% efficiency, 700 mV open-circuit voltage, 11.04 mA cm⁻² short-circuit current density, and 71.2% fill factor under 1000 W m⁻² irradiation. In contrast, the DSSC improved by graphene exhibited 6.8% efficiency, 13.4 mA cm⁻² short-circuit current density, 770 mV open-circuit voltage, and 66.2% fill factor under 1000 Wm⁻² irradiation. Furthermore, the efficiency and fill factor increase were observed when the irradiance decreased. The DSSC exhibited a remarkable efficiency of 9.4% under 67 W m⁻² irradiance. Achieving higher efficiency for quasi-solid-state configuration without relying on volatile solvent-based electrolytes is another significance of this study. The study uncovers that the strategic incorporation of graphene, synthesized in an economically viable manner, into specific layers of the photoanode significantly enhances the power conversion efficiency in DSSCs.

T. M. W. J. Bandara awijendr@yahoo.com; wijendra@sci.pdn.ac.lk

- ¹ Department of Physics and Postgraduate Institute of Science (PGIS), University of Peradeniya, Peradeniya, Sri Lanka
- ² Department of Natural Sciences, University of West Georgia, Carrollton, USA
- ³ National Institute of Fundamental Studies, Kandy, Sri Lanka



Graphical Abstract

Keywords Graphene solar cell · Low light · Efficiency enhancement · Dye solar cells · Graphene · Multilayer photoanode

1 Introduction

One of the biggest challenges in the twenty-first century is to replace fossil fuels with renewable and more environmentally friendly energy sources while supplying the ever-increasing energy demand. The development of lowcost and efficient solar cells with emerging technologies is the long-term solution to this energy crisis [1, 2]. Due to the lower production costs and the relatively high power conversion efficiency (PCE), dye-sensitized solar cells (DSSCs) have received greater attention from researchers during the last decade [3–5]. DSSCs have attained a maximum power conversion efficiency of 15.0% liquid electrolytes under ambient conditions [4]. The photoanode in a DSSC plays a key role in absorbing light energy and producing current and voltage through photoexcitation. The photoanode consists of a transparent conductive oxide (TCO) layer coated on a glass substrate. On top of this layer lies the mesoporous nanocrystalline wide-bandgap semiconducting material (TiO₂). Figure 1 depicts the structure and working mechanism of a dyesensitized solar cell. The power conversion efficiency of a DSSC is basically governed by the properties of the photoanode. A high-performing photoanode should have a large specific surface area for more dye adsorption, faster electron transport, high resistance to photo-corrosion, high electrical conductivity, and excellent interfacial contact between the dye molecules and the electrolyte [6, 7]. By integrating highly conductive carbon nanostructures, such as graphene,



Fig. 1 Schematic representation of the components and of the basic operating principle of a DSC

graphene oxide, carbon nanotubes, and fullerene into TiO_2 photoelectrode, DSSC performance can be enhanced due to the improved charge transport properties of the TiO_2 composite electrode. Among these carbon materials, graphene stands out due to its remarkable properties, such as excellent optical transmittance, tunable bandgap, high specific surface area, and high mechanical strength. Further, with the addition of graphene or graphene quantum dots, the PCE of DSSCs can be improved through up-conversion and down-conversion [8–10], broadening the spectral absorption of the photoelectrode [11], and improving electron mobility.

There are five major steps involved in the operation of a DSC. Figure 2 depicts a schematic diagram to represent the energy diagram and working principle of a DSC.

When light hits the DSC, the dye molecules absorb the photons, causing electrons to jump from a lower energy state (HOMO) to a higher energy state (LUMO)

$$S + hv \to S^*. \tag{1}$$

Next, the excited electrons inject from the dye to the conduction band of titanium dioxide, leaving the dye positively charged (oxidized).

$$\mathbf{S} * \to \mathbf{S}^+ + e^- (\mathrm{TiO}_2) \tag{2}$$

The excited electrons travel through the titanium dioxide and reach the conductive layer. These electrons then flow through an external circuit, producing electrical current.

$$e^-$$
 + TiO₂(CB) \rightarrow TiO₂ + e^- (CB) + electrical energy (3)



Fig. 2 Schematic representation of the energy diagram and basic operating principle of a DSC

Meanwhile, the positively charged dye molecules regain their electrons from the electrolyte, restoring their original state (Regeneration of the dye).

$$2S^+ + 3I^- \rightarrow 2S + I_3^- \tag{4}$$

Finally, the oxidized redox couple regenerates at the cathode by accepting electrons from the cathode (Electron capture).

$$I_3^- + 2e^- \to 3I^- \tag{5}$$

In the meantime, as this energy generation happens, recombination reactions also occur, which will result in a degradation of the energy generation rate of the DSC. In Fig. 2, (steps I and II) represent these recombination reactions. Three main types of recombination can occur inside a DSC:

- I. Electron recombination by donating electrons to oxidized dye rather than going through an external circuit.
- II. Electron recombination by donating electrons to oxidized redox couple.
- III. Relaxation of the excited dye molecules to the ground state via a non-radiative decay process.

These recombination reactions are needed to be overcome when enhancing the performance of a DSC [12].

Fang et al. first [13] reported graphene quantum dot (GQD)-assisted dye-sensitized TiO₂ photoelectrodes demonstrating an efficiency of 6.10%, making 19.6% enhancement with GQD inclusion. Fan et al. [14] reported a TiO₂/ graphene nanocomposite-based DSSC with 5.77% efficiency, which is a 25% enhancement over graphene-free cell. This efficiency improvement is attributed to reduced electrode-electrolyte interfacial resistance, diminished charge recombination rates, enhanced light scattering, and the enhancement of charge transport resulting from the addition of graphene. Pattarith et al. [15] report a higher efficiency of 9.15% for the cell optimized using graphene, benefiting from enhanced dye loading, improved electronic conductivity, and reduced recombination. For optimized TiO₂ photoelectrodes with RGO and graphene, Tang et al. [16] achieved a stateof-the-art efficiency of 11.8% for optimized TiO₂ photoelectrodes with reduced graphene oxide (RGO) and graphene. The reported higher efficiency is related to enhance light scattering and the increased surface area for dye adsorption. Murugesan et al. reported various nanocomposites to fabricate the photoanodes in DSCs. The study revealed an efficiency of 8.76%, for the amine-grafted TiO₂ nanowires and graphene nanocomposite photoanodes [17] and an efficiency of 8.18% was achieved using ethylenediamine functionalized graphene oxide (GO/NH₂), titania nanotubes (TiO₂ NTs), and 3 wt.% of Ag nanoparticle-based photoanodes [18]. The same researcher was able to achieve relatively higher power conversion efficiencies of 6.78% [19], 5.42% [20], and 5.11% [21] using various nanocomposites for the photoanodes. Table 1 summarizes the photovoltaic parameters of the state-of-the-art DSCs reported based on various architectures of TiO₂ and graphene.

The performance of a DSSC or any other solar cell mainly depends on the intensity of photon flux/solar irradiation incident to the cell. In nature, sunlight intensity does not remain constant throughout the day or year. Some studies have

Table 1 The values for the open-circuit voltage (V_{oc}) , short-circuit current density (J_{sc}) , fill factor (*ff*), and PCE of the DSCs prepared with various electrode configurations using graphene and TiO₂

Electrode configuration	V _{oc} /mV	J _{sc} /mA cm ⁻²	ff	PCE/%	Ref
TiO ₂ /SnO ₂ /Graphene	650	9.03	0.58	3.37	[22]
N-TiO ₂ /Graphene	710	15.38	0.46	5.01	[23]
GQD/TiO ₂	660	14.07	0.59	6.10	[24]
Graphene/TiO ₂	690	16.29	0.62	6.97	[25]
rGO/TiO ₂	630	25.02	0.54	8.51	[26]
Ag/rGO/TiO ₂	780	14.30	0.82	9.15	[15]
rGO/Graphene/TiO ₂	710	26.00	0.64	11.80	[<mark>16</mark>]

N- TiO_2 Nitrogen-doped TiO₂, GQD Graphene quantum dots, rGO Reduced graphene oxide

shown that the efficiency of traditional Si-based solar cells decreases with the decreasing irradiance level [27, 28]. Only a few studies have been focused on investigating the performance of quasi-solid-state DSSCs as a function of light intensity [29]. In addition, to our knowledge, there are no reported studies focused on investigating the performance of graphene-incorporated photoanode-based quasi-solid-state DSSC. Therefore, it is very important to investigate DSSC performance variation with the light intensity in order to estimate the power generation at different times of the day.

In addition to graphene and graphene oxide, various other carbon-based materials have also been explored for improving photoanodes in DSSCs. However, each presents its own unique set of advantages and disadvantages. Carbon nanotubes (CNTs), for instance, have gained attention due to their exceptional electrical conductivity, high surface area, and tubular structure [30, 31]. However, challenges such as CNT aggregation and the difficulty of achieving uniform distribution on photoanodes may have impacted their effective utilization in DSSCs. Carbon nanofibers (SNFs) are one-dimensional nanostructures similar to CNTs with good electrical conductivity and mechanical strength [32]. Despite their advantages, challenges in synthesizing and difficulty in proper alignment within the photoanode are considerable drawbacks. Carbon aerogels, a three-dimensional porous carbon structure, offer a large surface area for dye adsorption and electron transport [33].

According to the literature, while relatively higher efficiencies are recorded for graphene-added DSSCs compared to control devices, the highest efficiency achieved (15%) by conventional DSSCs has not yet been surpassed. Additionally, the complexity of synthesis and poor stability and scalability issues hindered their application. This field necessitates further research to develop effective strategies for integrating carbon-based materials such as graphene into DSSC photoanodes to address these challenges.

By taking the above-mentioned key factors into account, the present study focuses on systematically incorporating a small amount of graphene into the multilayer photoanode. Interestingly, in this study, the integration of graphene into the 4th layer of the 6-layer TiO_2 photoanode resulted in enhanced solar cell performance. In addition, one of the challenges of utilizing graphene in solar cells is their high cost. This study presents a low-cost, feasible, and novel method for synthesizing graphene using vein graphite received directly from the mine site for incorporation into photoanodes. Another significance of this study is achieving higher efficiency for quasi-solid-state configuration without relying on volatile solvent-based electrolytes in the DSSCs.

2 Experimental

2.1 Materials

Transparent and conducting FTO substrates having a sheet resistance of 10 Ω cm⁻² and ruthenium-based 535-bisTBA (N719) dye sensitizer were purchased from Solaronix SA. Titanium dioxide nanopowders of average particle sizes of 21 nm (P25) and 13 nm (P21) were procured from Evonik, Germany. The starting materials for the preparation of the gel polymer electrolyte such as iodine (I₂), ethylene carbonate (EC), propylene carbonate (PC), 1-methyl-3-propylimidazolium iodide (MPII), and 4-tert-butylpyridine (4-TBP) with purity greater than 98%, tetrahexyl ammonium iodide, lithium iodide, and polyethylene oxide (MW = 4,000,000) were purchased from Sigma-Aldrich. Before use, tetrahexyl ammonium iodide, lithium iodide, and polyethylene oxide (PEO) were vacuum dried for about 2 h at 50 °C.

2.2 Preparation of graphene

Graphene can be synthesized using various methods for applications [34]. In this study, the electrolyte solution for the exfoliation was prepared by dissolving 26.14 g of K_2SO_4 in 300 mL of deionized water (0.5 M). Shiny slippery fibrous (SSF) natural Sri Lankan vein graphite obtained from the Kahatagaha mine site mining site was used as starting material [35]. Two pieces of vein graphite samples were directly used as the anode and cathode. The separation between the two electrodes was kept at about 3 cm, and electrochemical exfoliation of graphite was conducted by applying a 10 V (DC) between the two graphite electrodes for 2 h. After that, the layer floating on the top of exfoliated graphite (EG) suspension was collected and filtered using a PTFE membrane filter (0.2-µm pore size). Then, the EG was washed several times with DI water to remove residual salt, and it was placed in the oven at 80 °C for 3 h.

For further exfoliation, 1 g of electrochemically EG was added to 100 ml of DMF, and it was sonicated for 3 h in order to synthesize graphene as already reported [36]. After

the sonication, the solution was stirred with the help of a magnetic stirrer for 24 h in order to further minimize the particle size. The resulting solution was then oven-dried and the precipitate was used for the characterization and solar cell fabrication.

2.3 Preparation of graphene-added multilayer photoelectrode

For the preparation of 1st and 2nd layers of TiO₂ photoanode, 0.5 g of TiO₂ nanoparticles with an average particle size of 13 nm (P90 powder) was mixed with 0.1 mol dm⁻³ HNO₃ for about 30 min in an agate mortar with a pestle. In order to prevent the coating of TiO₂ in the area needed for FTO contacts, half of the FTO electrode was masked with scotch tape. Then, the TiO₂ slurry was spin-coated on a wellcleaned FTO substrate of 1 cm × 2 cm size at 2300 rpm for 2 min. For this purpose, freshly prepared TiO_2 slurry was spread homogeneously on the FTO substrate with the help of a pestle, and spinning commenced immediately after the application of the TiO₂ slurry on the glass substrate, without allowing time for it to dry. Subsequently, the photoelectrode was air-dried at ambient conditions for 24 h and then sintered in air at about 450 °C for 30 min. For the preparation of the 3rd layer of the photoelectrode, 0.5 g of TiO₂ nanoparticles of particle size 21 nm (P25) was ground with 0.1 mol dm⁻³, and the resulting slurry was spin-coated at 1000 rpm for 2 min and followed by sintering at 450 °C.

The 4th, 5th, and 6th TiO_2 layers were prepared following the spin coating and sintering process used for the 3rdlayer preparation, except that 0.1 g of PEO (4,000,000 molar weight) and a few drops of Triton X 100 (surfactant) were added to the TiO₂ slurry and then well-grounded before the spin coating is carried out. In order to optimize the test cells with graphene-added electrodes, preliminary studies were conducted to select suitable layers and find appropriate graphene content. Preliminary observations confirmed that the addition of 1% of graphene to the slurry used for 4th-layer preparation gives solar cells performance enhancement.

The improved (graphene-added) 4th layer was prepared following the spin coating and sintering process used for the preparation of the 4th layer. To prepare the graphene-added photoanode, 0.005 g of graphene was added to the TiO_2 slurry and then well-grounded prior to spin coating. This slurry was used to coat the 4th layer of the photoelectrode. The configuration of the photoanode prepared with 6 successive layers of spin-coated TiO_2 nanoparticle layers is illustrated schematically in Fig. 3.

2.4 Preparation of the gel polymer electrolyte

The optimized gel polymer electrolyte was prepared as per the stoichiometric composition of





Table 2 The weight composition and molar ratios of polymer (PEO), solvents (EC and PC), performance enhancers (MPII and 4-TBP), and iodide salts in the gel polymer electrolyte

Component	Weight/mg	Molar ratio
PEO	100.0	10.0
PC	927.0	40.0
EC	800.0	40.0
MPII	15.1	0.25
Hex ₄ NI	87.5	0.80
LiI	36.5	1.20
4-TBP	26.1	0.85
I_2	11.5	0.20

 $(EO)_{10}(EC)_{40}(PC)_{40}LiI_{(1.2)}(Hex_4NI)_{(0.8)}(4\text{-}TBP)_{(0.85)}(MPII)_0\\ {}_{25}I_{2(0.2)}, \text{ where the abbreviation EO represents one monomer unit of the polymer PEO [37].}$

As the initial step for the preparation of the electrolyte, appropriate amounts of Hex_4NI , LiI, MPII, and 4-TBP were dissolved in the PC and EC co-solvent mixture in a closed vial. Then, after adding the appropriate amount of PEO, the mixture was stirred continuously until a homogeneous mixture was obtained. Afterward, the mixture was heated up to 100 °C with constant stirring until it was converted into a transparent slurry. Finally, the mixture was cooled down to 40 °C, 1_2 (11.5 mg) was added, and the mixture was stirred well. The resulting gel polymer electrolyte from this process was characterized and then utilized for solar cell fabrication. The relevant molar ratios and weights for the electrolyte are given in Table 2.

2.5 Fabrication of the DSSC

Two different DSSCs were assembled by sandwiching the gel polymer electrolyte between a Pt-coated glass counter electrode and a dye-sensitized TiO_2 photoelectrode with 6 spin-coated TiO_2 layers. One DSSC contained the photoelectrode prepared by incorporating graphene into the 4th layer.

3 Characterization

3.1 Characterization of the photoelectrode

The X-ray diffraction (XRD) technique was utilized for crystallographic characterization of the photoanode. Cu K- α radiation wavelength 1.5405 Å from the Rigaku Ultima-IV X-Ray Diffractometer (KYOWAGLAS-XATM, Japan) was used to generate the XRD patterns of the TiO₂ film. In order to get the XRD spectrum, two single-layer electrodes were prepared with and without graphene in the same way the 4th layer was prepared.

The scanning electron microscopic (SEM) images of the TiO_2 film were taken using Zeiss EVO-LS15 SEM. These images of the films were used to investigate the morphology of the TiO_2 films and the thickness of the photoanode.

3.2 Characterization of the DSSC

Finally, the fabricated DSSCs were irradiated with PEC-LO1 solar simulator. By keeping the active area of the cell at 19 mm² and by varying the light intensity, current–voltage (*I–V*) data were measured with a potential scan rate of 10 mV s⁻¹ using Keithley 2400 sourcemeter and Pecell software. The light intensity was varied by changing the distance from the solar simulator to the cells. The obtained data were used to calculate the solar cell performance parameters *J*sc, V_{oc} , *ff*, and the PCE of the cell.

The PCE of the cell at variable intensity levels is calculated as follows:

$$PCE = \frac{P_{max}}{I} \tag{6}$$

where P_{max} is the maximum power output of the cell and *I* is the irradiance of the incident light. The fill factor (*FF*) of the cell was determined as follows:

$$FF = \frac{P_{max}}{V_{OC}J_{SC}} \tag{7}$$

Therefore,

$$PCE = \frac{FFV_{OC}J_{SC}}{P_{solar}}$$
(8)

Equation (8) is used to calculate the intensity-dependent PCE values which are tabulated in Tables 3 and 4.

3.3 Electrochemical impedance spectroscopy

Electrochemical impedance spectroscopy (EIS) data of the solar cells and electrolytes were measured by a Potentiostat (Autolab PGSTAT128N) together with a frequency response analyzer (FRA) module. Impedance data were collected with NOVA 1.1 software. During the measurements, the cells were placed in a Faraday cage. The EIS measurements of solar cells were done by applying a bias voltage similar to the V_{oc} of the respective cells. To get EIS data of electrolytes, sample cells were prepared by sandwiching the electrolyte between two stainless steel electrodes. The measurement frequency window was 0.1 Hz–1000 kHz and scanning was conducted with 80 steps.

4 Results and discussion

Table 3 Calculated values for the V_{OC} , J_{SC} , f, η , and the maximum power of the cell under different irradiation levels for cells prepared without adding graphene to the 4th layer

Understanding the variation in electrical conductivity of PEO-based electrolytes with temperature is crucial for optimizing electrolytes for different operating conditions.

The ionic conductivities were calculated using the complex impedance data provided in Fig. 4a. The Arrhenius equation aids in predicting conductivity trends and provides insights into the activation energy of charge carriers. The ionic conductivity obtained using complex impedance measurements is depicted in Fig. 4b as a function of 1000/T, where *T* represents the electrolyte temperature. The top axis of the plot in Fig. 4b specifies the electrolyte temperature. The electrolyte exhibits an ionic conductivity of 3.37 mS cm⁻¹ at 293.0 K, which increases to 7.31 mS cm⁻¹ at 353.0 K. The data presented in Fig. 4b were fitted to the following equation:

$$\sigma = A \exp\left(-\frac{E_a}{K_B T}\right) \tag{9}$$

where σ , *A*, *E_a*, and *K_B* represent the conductivity, the preexponential factor, the activation energy, respectively, and the Boltzmann constant. The obtained values for the *E*a and *A* by linear fitting to Eq. 4 are 51.6 meV and 0.48 S cm⁻¹, respectively.

Intensity / W m ⁻²	$V_{\rm oc}/{ m V}$	$J_{\rm sc}/{\rm mA~cm^{-2}}$	$V_{\rm opt}/V$	$J_{\rm opt}/{\rm mA~cm^{-2}}$	$P_{\rm max}/{\rm W}$	ŋ/%	<i>ff</i> /%
1108	0.7	12.3	0.53	11.3	5.98	5.39	69.6
1000	0.7	11.0	0.53	10.38	5.5	5.50	71.2
607	0.7	7.24	0.53	6.80	3.61	5.94	71.2
381	0.69	4.56	0.54	4.25	2.30	6.02	72.9
251	0.68	3.13	0.54	2.92	1.58	6.29	74.1
180	0.67	2.24	0.54	2.11	1.14	6.33	76.1
136	0.66	1.67	0.54	1.60	0.86	6.35	78.2
104	0.65	1.32	0.54	1.25	0.67	6.48	78.7
85	0.64	1.08	0.54	1.04	0.56	6.59	80.9
67	0.63	0.87	0.55	0.81	0.45	6.68	81.5

Table 4 Calculated values for the V_{OC} , J_{SC} , f, η , and the maximum power of the cell under different irradiation levels for cells prepared by adding graphene into the 4th layer

Intensity /W m ⁻²	$V_{\rm oc}/V$	$J_{\rm sc}/{\rm mA~cm^{-2}}$	V _{opt} / V	$J_{\rm opt}/{\rm mA~cm^{-2}}$	$P_{\rm max}/{\rm W}$	ŋ/%	ff 1%
1108	0.74	17.0	0.47	15.2	7.12	6.43	56.5
1000	0.77	13.4	0.54	12.6	6.82	6.82	66.2
607	0.71	9.69	0.50	8.97	4.49	7.40	65.2
381	0.71	6.34	0.52	5.92	3.08	8.07	68.3
251	0.70	4.20	0.53	3.98	2.11	8.41	71.9
180	0.69	3.02	0.54	2.88	1.55	8.62	74.5
136	0.69	2.27	0.55	2.17	1.20	8.79	76.3
104	0.68	1.73	0.55	1.70	0.94	9.01	79.5
85	0.68	1.42	0.55	1.42	0.78	9.23	81.3
67	0.68	1.11	0.55	1.15	0.63	9.40	83.1



Fig. 4 a Complex impedance plots of the electrolyte at different temperatures; b the graph of conductivity (σ) versus 1000/T obtained using complex impedance measurements

4.1 XRD measurements

The XRD pattern for the 4th layer prepared with TiO_2 and graphene is given in Fig. 5. The 2θ values along with relevant TiO_2 phases and crystal planes are marked. Most of the peaks correspond to the dominant anatase phase of TiO_2 (101, 004, 200), and the presence of several characteristic peaks in the XRD spectra provides evidence for the



Fig. 5 XRD spectra of the 4th layer prepared with **a** TiO_2 and 1% graphene and **b** TiO_2 only

polycrystalline nature of the TiO_2 films. Peaks (110) and (101) correspond to the rutile phase of TiO_2 , and the origin of the peak (110) FTO is due to the diffraction pattern associated with FTO glass. In comparison, (101)A, (111) R, and (200)A peaks have become broader for graphene-free samples, which can be attributed to the smaller size of crystallites or an increase in lattice defects in graphene-free samples. Furthermore, the intensity of reflection from the (004)A plane has diminished in the graphene-free sample since it is not a preferred orientation of the sample.

In Fig. 5a, the peak related to graphene is clearly seen at (001) crystal plane. However, the intensity of the peak is not as strong as TiO₂ peaks because only 0.005 g (1% w/w) of graphene has been used to fabricate the photoanode. The absence of significant carbon peaks can be due to the dominance of TiO₂ content (99%) in the electrode.

4.2 Raman spectroscopy

Figure 6 shows the Raman spectra of the exfoliated graphene. Two dominant peaks are visible, namely the G band and 2D band at intensities of 1580 cm⁻¹ and 2730 cm⁻¹, respectively. The occurrence of the G band is due to the stretching vibrational motion of SP² hybridization of carbon–carbon bonds, and the peak position occurs at 2730 cm⁻¹ is a characteristic signature of graphene [36].

The number of layers in exfoliated graphene was calculated using the intensity ratios between 2D and G peaks (I_{2D}/I_G) . According to the experimental results, the value obtained for the I_{2D}/I_G ratio is 1.43. This data confirmed the successful synthesis of double-layered graphene [36]. This exfoliated double-layered graphene synthesized directly from vein graphite is used to fabricate the photoanodes of the solar cells investigated in this study.



Fig. 6 Raman spectra of the exfoliated graphene samples

SEM images of the fabricated photoelectrodes at a magnification of 100,000 are shown in Fig. 7. Figure 7a shows the top surface morphology of a 4-layer photoelectrode fabricated without graphene in the 4th layer, while Fig. 7b shows the improved photoelectrode by adding graphene to the 4th layer. When comparing the morphologies of these two layers, it can be observed that 4-layered electrodes prepared by adding graphene to the 4th layer (Fig. 7b) consist of graphene sheets. The presence of graphene in the 4th layer can enhance the conductivity in the photoelectrode and alter the dye adsorption properties as well as influence the photocurrent, PCE, and fill factor of the DSSCs. Also, the presence of graphene may minimize the charge transfer resistances at the interfaces of the TiO₂ layer by faster electron transport, which can hinder recombination. In addition, graphene can contribute to efficiency enhancement by improving light scattering as well.

Figure 7c and 4d shows the top surface morphology of the two 6-layer photoelectrodes prepared without and with graphene to the 4th layer, respectively. These images confirm the formation of crack-free, nanocrystalline mesoporous thin films with high porosity that offer a large surface area for dye absorption. As we can see, these two images (Fig. 7c and 4d both look identical in the surface morphology, because the same procedures and steps have been repeated to fabricate the 6th-layer electrodes except for the 4th layer. The image in 4(d) confirms there are no graphene sheets visible. Therefore, the graphene in the 4th layer is well covered by the 5th and 6th TiO₂ layers.

4.3 Dependence of cell performance on irradiance level

Solar cell characteristics were evaluated as a function of intensity by taking I-V characteristic curves. Both graphene-added and graphene-free cells exhibited typical dyesensitized solar cell behavior but with variations in their parameters. The plots for current density vs. cell potential (J-V) and power density vs. cell potential (P-V) are shown in Fig. 8. The J-V and P-V curves of the graphene-added DSSCs at each intensity level are given in Figs. 8a and b, respectively. The J-V and P-V curves of the graphene-free control DSSCs at each intensity level are shown in Figs. 8c and d, respectively. The photocurrent density and output power density of both cells decrease with decreasing intensity due to the reduction of photon flux, resulting in low photoelectron generation.

The J-V and P-V characteristic curves in Fig. 8 are used to determine the open-circuit voltage (V_{oc}), the short-circuit current density (J_{sc}), the fill factor (ff), and the PCE of the fabricated DSSC under different irradiation levels. The values calculated for graphene-free DSSC (control cell) at different intensity levels are given in Table 3, while the



Fig.7 a The SEM image of the 4th layer of the TiO_2 electrode prepared without adding graphene. **b** SEM image of the 4th layer of the electrode prepared by adding graphene to the 4th layer. SEM images

respective values for the graphene-added cell (test cell) are given in Table 4.

The cell fabricated without graphene in the 4th layer exhibited significantly low performance compared to that of the graphene-added cell. The fabricated DSSC without graphene achieved 5.39% efficiency under 1108 W m⁻² irradiance, while that in graphene-added cell is 6.43%. With the gradual decrease of light irradiance level, the PCE of the cells increases, although the net power output drops. This PCE increase observed in both cells with decreasing irradiance is attributed to an increase in fill factor, which indicates the decrease in resistive losses (Tables 3 and 4). For example, the PCEs of graphene-free and graphene-added cells increase from 5.05% to 6.82% under one sun illumination (1000 W m⁻²). Consequently, the highest PCE and ff are exhibited at the lowest tested irradiance level of 67 W m⁻². The PCEs of graphene-free and graphene-added cells increase to 6.68% and 9.40% under 67 W m⁻² intensity level.

of the 6-layer photoanodes prepared c without adding graphene and d SEM image of the top (6th) layer of the electrode prepared by adding graphene to the 6th layer

With the results obtained from both cells, it is evident that the efficiency and fill factor of the DSSCs increase with the decrease of irradiation. Achieving higher efficiencies in dyesensitized solar cells under low-light intensities agrees with the literature [38–40].

Further in both the cells, *ff* has increased with decreasing light intensity. It can be due to reduced recombination kinetics, non-radiative thermalization losses, and charge transport losses. At the lower intensities, the generation of electron-hole pairs in the photoelectrode is less. This decreases the probability of carrier recombination before reaching the electrodes. Therefore, cells exhibit higher photocurrent at maximum power output, contributing to a higher fill factor. At lower intensities, a smaller number of photons are available to excite electrons. Therefore, along with decreasing carrier generation and associated non-radiative recombination and thermalization of charge carriers they decrease contributing to enhance the fill Fig. 8 a Current density vs. cell potential curves for the cell prepared without graphene. b Current density vs. cell potential curves for the cell prepared by adding graphene to the 4th layer. c Power density vs. cell potential curves for the cell prepared without graphene. d Power density vs. cell potential curves for the cell prepared by adding graphene to the 4th layer



factor. Since current and number of charge carriers at lower light intensities are less, the resistive losses due to diffusion and the resistances are low and hence, a higher fill factor can be expected.

4.4 Incident photon-to-current efficiency (IPCE)

IPCE measurements offer valuable insight into the spectral response and performance of a DSC across the solar

Fig. 8 (continued)



spectrum. By varying the wavelength of the incident light, the obtained IPCE spectra for the two distinct variants of the fabricated solar cells are given in Fig. 9. The reference solar cell is composed of a photoanode solely made of TiO_2 nanoparticles, which provides a baseline for comparison. During characterization, it exhibits moderate IPCE values with a single narrow absorption peak.

This graphene-free cell exhibits a maximum IPCE of 40.65 at 525 nm. The test cell, enhanced with graphene, shows higher IPCE with two distinctive peaks at ~ 345 nm and ~ 530 nm, along with IPCE of 44.35 and 53.76%. The IPCE value is usually determined by the charge collection at the collecting electrode and dye loading capacity. With added graphene on TiO_2 it could capture and shuttle





electrons quickly to the collecting electrodes, which leads to the improvement of the IPCE value of the graphenebased solar cell over the entire wavelength of the spectrum [41, 42].

4.5 Electrochemical impedance (EIS) spectroscopy

In order to get further insight into the higher efficiency of the test cell, EIS data are utilized. Figures 10a and 8b represent the Nyquist plots and Bode phase diagrams for the two cells. Using the impedance spectra, Bode diagram was



Fig. 10 a The Nyquist plots and b the Bode phase diagrams for the two prepared DSCs

Table 5 Recombination lifetimes (τ_{rec}), electron transport lifetimes (τ_{tr}), and diffusion lengths (D_L) of the prepared DSCs

(<i>L</i>)/µm	$\tau_{\rm rec}/{ m mS}$	$\tau_{\rm tr}/{ m mS}$	$D_{\rm L}/\mu{\rm m}$
5.2	3.22	0.34	7.1
5.2	2.43	0.25	6.2
	(<i>L</i>)/μm 5.2 5.2	(L)/μm τ _{rec} /mS 5.2 3.22 5.2 2.43	(L)/µm τ_{rec}/mS τ_{tr}/mS 5.2 3.22 0.34 5.2 2.43 0.25

plotted and estimated. The values of electron transport lifetime (τ_{tr}), recombination lifetime (τ_{rec}), and diffusion length (D_{L}) are given in Table 5.

The $D_{\rm L}$ is the average distance traveled by a charge carrier within the semiconducting material before it recombines. This length plays a crucial role in determining the efficiency of charge carrier transport and lifetime inside the cell. In this study, $D_{\rm L}$ was calculated by following the equation, along with the impedance data analysis [43–45].

$$D_L = L \sqrt{\frac{R_{rec}}{R_{tr}}}$$

where R_{tr} and R_{rec} represent the charge transfer resistance and recombination resistance. *L* is the layer thickness [46]. Nyquist plots in Fig. 10a were used to determine the R_{tr} and R_{rec} for each cell and layer thickness was measured using high-resolution scanning electron microscopy ($L=5.2 \mu m$).

Interestingly, the study shows the DSC fabricated with TiO₂ and graphene has a higher diffusion length value than that of the reference cell. The increased diffusion length enhances the likelihood that the charge carriers will reach the electrodes, contributing to enhancing collection efficiency. In a DSC, photogenerated electrons and holes are separated at the dye-semiconductor interface. However, a certain number of charge carriers recombine instead of traveling through the external circuit, which could negatively impact the overall performance of the solar cell. By increasing the recombination lifetimes, it is possible to prolong the duration of which these electron-hole pairs remain separated. This prolonged duration allows more charge carriers to reach the electrodes and contribute to the photocurrent. The study shows the fabricated solar cell with TiO₂ and graphene contains higher recombination lifetimes compared to the reference cell. This longer lifetime may have impacted positively to improve cell efficiency.

4.6 Effect of graphene on cell performance

The cell fabricated by adding graphene shows higher V_{OC} , J_{SC} , ff, and PCE compared to the cell without graphene. The observed performance enhancement is very likely due to the



Fig. 11 a Efficiency variation of the cells with light intensity. b Variation of the fill factor of the cells with light intensity

positive effects imposed by the incorporated graphene. For a better visualization of the behavior, PCE and ff variations of the cells with light intensity are shown in Fig. 11a and b, respectively.

Graphene has excellent electrical conductivity and optical properties, enabling it to enhance the absorption of light and facilitate efficient charge transport within the solar cell, leading to higher conversion efficiencies and increased power output. The improved performance with added graphene observed in this study can be attributed to the combined effects of the following process.

- 1) Decreased charge transport resistance of the photoelectrode and charge transfer resistance between two interfaces of TiO_2 as a result of increased conductivity [47, 48]. The reduction of resistive losses improves the photocurrent of the cell. The decrease of resistive losses with added graphene is inferred by the higher *ff* shown by the graphene-incorporated cell.
- 2) The improved charge transfer between the FTO current collectors indirectly helps to reduce the recombination losses. The behavior is evident by the increase of V_{OC} and *ff* of the graphene-added cell. This process enables more efficient conversion of light energy to electricity.
- 3) The $V_{\rm oc}$ enhancement can be contributed by faster electron extraction by graphene-added interlayer from the excited dye molecules [49, 50]. Graphene's large surface area and high carrier mobility facilitate improved electron injection from the excited dye molecules to the

Table 6 Efficiency enhancements by the graphene-incorporated photo electrode-based DSSCs with respect to the graphene-free solar cell

Intensity/W m ⁻²	1108	1000	607	381	251	180	136	104	85	67
Efficiency enhancement /%	19.3	24	24.6	34.1	33.7	36.2	38.4	39.0	40.1	40.7

Graphene/TiO₂ layer, thereby enhancing the efficiency of the dye-to-photoelectron conversion process. This can also reduce energy loss due to non-radiative decay.

4) Graphene's large surface area can facilitate the distribution of TiO_2 and thus enhance the effective surface area available for dye adsorption by the electrode, as inferred by analyzing SEM images. This promotes higher dye loading, leading to increased light absorption and improved device performance.

Finally, it can be deduced that the DSSC made with graphene-added photoelectrode exhibited impressive efficiency enhancement under low irradiation. For instance, the addition of 1% of graphene to the 4th TiO_2 layer of the photoanode improves the efficiency of the cell from 5.50% to 6.82% under one sun illumination (1000 W m⁻²). This is a 24% efficiency improvement. Efficiency enhancements given by the graphene-added DSSC with respect to graphene-free solar cells (control device) are given in Table 6 for different irradiance levels.

The present study shows that not only graphene can be used to enhance DSSC performance but also that graphene can be successfully synthesized from natural vein graphite using a scalable and cost-effective method.

5 Conclusion

This study reports efficiency enhancements in grapheneincorporated, quasi-solid-state DSSCs under ambient and low-light conditions. The XRD results and high-resolution SEM images confirmed the presence of anatase TiO_2 nanoparticles in photoelectrodes. The Raman spectroscopy confirmed the successful fabrication of two-layer graphene from the vein graphite. One of the challenges of widely utilizing graphene in solar cells is their high cost. This study presents a cost-effective, feasible, and novel method to exfoliate vein graphite sourced directly from the mine site and a strategic way to integrate them in photoanodes. SEM images confirm the presence of graphene in the most effective layer of the photoanode.

The PCEs of 5.05% graphene-free cells (control cell) increased to 6.82% with the integration of graphene into the photoanode, exhibiting 24% enhancement at ambient irradiation. The V_{oc} , J_{sc} , and ff, values of graphene-incorporated DSSC are 6.82%, 770 mV, 13.4 mA cm⁻², and 66.2% respectively, at 1000 W m⁻². Notably, the efficiency and fill factor

exhibited an intriguing increase at lower light intensities. The synthesized graphene-incorporated DSSC achieved a remarkable efficiency of 9.4% and a fill factor of 83.1% at 67 W m⁻² solar irradiance. The efficiency enhancement for 67 W m⁻² intensity compared to 1000 W m⁻² is ~ 38%.

The performance of the improved DSSC by integrating the synthesized graphene from vein graphite outperforms the reference cell at all the intensities measured. This improved efficiency is attributed to the higher charge carrier recombination lifetime (3.22 mS) and high diffusion lengths (7.1 μ m) of the improved DSC by integrating graphene into to photoanode.

Acknowledgements The authors would like to acknowledge Udara Wadasinghe in University Peradeniya, for the technical support given for this project.

Author contributions T.M.W.J. Conceptualization, Methodology, Project administration and Supervision, Writing, Reviewing Editing fund acquisition and Formal analysis. S.M.S.G. Data collection, Formal analysis and measurement, 1st draft preparation. G.G.D.M.G.G: Data collection, Formal analysis and measurement. B.M.K.P., Writing, Reviewing, Editing and Formal analysis. L.A.DeS., Writing, Reviewing, Editing and Formal analysis. M.A.K.L.D. and G.R.A.K., Writing, Reviewing, Editing and Formal analysis.

Funding The authors would like to acknowledge the financial support from the Postgraduate Institute of Science, University of Peradeniya (grant No. PGIS/2020/10), and Peradeniya University Research Grant No. 2023/34/S.

Data availability No datasets were generated or analysed during the current study.

Declarations

Conflict of interest The authors declare no competing interests.

References

- Mariotti N, Bonomo M, Fagiolari L, Barbero N, Gerbaldi C, Bella F, Barolo C (2020) Recent advances in eco-friendly and costeffective materials towards sustainable dye-sensitized solar cells. Green Chem 22(21):7168–7218
- Nishshanke GBMMM, Arof AK, Bandara TMWJ (2020) Review on mixed cation effect in gel polymer electrolytes for quasi solidstate dye-sensitized solar cells. Ionics 26:3685–3704
- Muñoz-García AB, Benesperi I, Boschloo G, Concepcion JJ, Delcamp JH, Gibson EA (2021) Dye-sensitized solar cells strike back. Chem Soc Rev 50(22):12450–12550
- Ren Y, Zhang D, Suo J, Cao Y, Eickemeyer FT, Vlachopoulos N, Zakeeruddin SM, Hagfeldt A, Grätzel M (2023) Hydroxamic

acid pre-adsorption raises the efficiency of cosensitized solar cells. Nature 613:60-65

- Bandara TMWJ, Hansadi JMC, Bella F (2022) A review of textile dye-sensitized solar cells for wearable electronics. Ionics 28(6):2563–2583
- 6. Ahmad MS, Pandey AK, Abd Rahim N (2017) Advancements in the development of TiO_2 photoanodes and its fabrication methods for dye sensitized solar cell (DSSC) applications. A review. Renew Sustain Energy Rev 77:89–108
- Galliano S, Bella F, Gerbaldi C, Falco M, Viscardi G, Grätzel M, Barolo C (2017) Photoanode/electrolyte interface stability in aqueous dye-sensitized solar cells. Energ Technol 5(2):300–311
- Ivaturi A, Upadhyaya H (2018) Upconversion and downconversion processes for photovoltaics. A comprehensive guide to solar energy systems. Academic Press, Cambridge, pp 279–298
- Zhuo S, Shao M, Lee ST (2012) Upconversion and downconversion fluorescent graphene quantum dots: ultrasonic preparation and photocatalysis. ACS Nano 6(2):1059–1064
- De la Mora MB, Amelines-Sarria O, Monroy BM, Hernández-Pérez CD, Lugo JE (2017) Materials for downconversion in solar cells: perspectives and challenges. Sol Energy Mater Sol Cells 165:59–71
- 11. Rühle S, Shalom M, Zaban A (2010) Quantum-dot-sensitized solar cells. ChemPhysChem 11(11):2290–2304
- Bandara TMWJ, Gunathilake SMS, Dissanayake MAKL, Pemasiri BMK, Albinsson I, Mellander BE (2024) A review of the development of graphene-incorporated dye-sensitized solar cells. Ionics. https://doi.org/10.1007/s11581-024-05752-6
- Fang X, Li M, Guo K, Li J, Pan M, Bai L, Luoshan M, Zhao X (2014) Graphene quantum dots optimization of dye-sensitized solar cells. Electrochim Acta 137(634):638
- 14. Fan J, Liu S, Yu J (2012) Enhanced photovoltaic performance of dye-sensitized solar cells based on TiO_2 nanosheets/graphene composite films. J Mater Chem 22(33):17027–17036
- Pattarith K, Areerob Y (2020) Fabrication of Ag nanoparticles adhered on RGO based on both electrodes in dye-sensitized solar cells (DSSCs). Renewables Wind Water Solar 7(1):1–10
- Tang B, Yu H, Peng H, Wang Z, Li S, Ma T, Huang W (2018) Graphene based photoanode for DSSCs with high performances. RSC Adv 8(51):29220–29227
- Kandasamy M, Selvaraj M, Kumarappan C, Murugesan S (2022) Plasmonic Ag nanoparticles anchored ethylenediamine modified TiO2 nanowires@ graphene oxide composites for dye-sensitized solar cell. J Alloy Compd 902:163743
- Kandasamy M, Selvaraj M, Alam MM, Maruthamuthu P, Murugesan S (2022) Nano-silver incorporated amine functionalized graphene oxide titania nanotube composite: a promising DSSC photoanode. J Taiwan Inst Chem Eng 131:104205
- 19. Pugazhenthiran N, Mangalaraja RV, Vijaya S, Suresh S, Kandasamy M, Sathishkumar P, Anandan S (2020) Fluorine-free synthesis of reduced graphene oxide modified anatase TiO_2 nanoflowers photoanode with highly exposed 0 0 1 facets for high performance dye-sensitized solar cell. Sol Energy 211:1017–1026
- Sasikala R, Kandasamy M, Suresh S, Ragavendran V, Sasirekha V, Pugazhenthiran N, Mayandi J (2023) Strontium titanate perovskite embedded reduced graphene oxide photoanode for dyesensitized solar cell. Opt Mater 136:113464
- Kandasamy M, Murugesan SJSE (2020) Aminosilicate modified mesoporous anatase TiO2@ graphene oxide nanocomposite for dye-sensitized solar cells. Sol Energy 211:789–798
- 22. Basu K, Selopal GS, Mohammadnezad M, Akilimali R, Wang ZM, Zhao H, Vetrone F, Rosei F (2020) Hybrid graphene/metal oxide anodes for efficient and stable dye sensitized solar cell. Electrochim Acta 349:136409

- Gao N, Wan T, Xu Z, Ma L, Ramakrishna S, Liu Y (2020) Nitrogen doped TiO2/Graphene nanofibers as DSSCs photoanode. Mater Chem Phys 255:123542
- Fang X, Li M, Guo K, Li J, Pan M, Bai L, Zhao X (2014) Graphene quantum dots optimization of dye-sensitized solar cells. Electrochim Acta 137:634–638
- Yang N, Zhai J, Wang D, Chen Y, Jiang L (2010) Two-dimensional graphene bridges enhanced photoinduced charge transport in dye-sensitized solar cells. ACS Nano 4(2):887–894
- Low FW, Lai CW, Abd Hamid SB (2017) Surface modification of reduced graphene oxide film by Ti ion implantation technique for high dye-sensitized solar cells performance. Ceram Int 43(1):625–633
- 27. Halm A, Hering P, Comparotto C, Koduvelikulathu LJ, Mihailetchi VD, Wefringhaus E, Kopecek R (2011) Low light intensity performance of n-and p-type silicon solar cells with different architectures. Proc. PVSEC-21
- Reich NV, Van Sark WGJHM, Alsema EA, Lof RW, Schropp REI, Sinke WC, Turkenburg WC (2009) Crystalline silicon cell performance at low light intensities. Sol Energy Mater Sol Cells 93(9):1471–1481
- 29. Domenici S, Speranza R, Bella F, Gatti T, Lamberti A (2024) Sustainable and non-toxic hydrogel-based dye-sensitized solar cells: performance evaluation under indoor illumination. In 245th ECS Meeting (2024). ECS
- Vindhyasarumi, Raman A, Sethulekshmi AS, Appukuttan S, Joseph K (2022) Carbon nanotube-based hybrid materials. Handbook of carbon nanotubes. Springer, Cham, pp 525–556
- Huang S, Du X, Ma M, Xiong L (2021) Recent progress in the synthesis and applications of vertically aligned carbon nanotube materials. Nanotechnol Rev 10(1):1592–1623
- 32. Zhou X, Wang Y, Gong C, Liu B, Wei G (2020) Production, structural design, functional control, and broad applications of carbon nanofiber-based nanomaterials: a comprehensive review. Chem Eng J 402:126189
- 33. Ma X, Xu Y (2022) Three-dimensional porous nitrogen-doped carbon aerogels derived from cellulose@ mof for efficient removal of dye in water. J Environ Chem Eng 10(5):108385
- Das S, Sudhagar P, Kang YS, Choi W (2015) Synthesis and characterization of graphene. Carbon nanomaterials for advanced energy systems: advances in materials synthesis and device applications. Wiley, New York, pp 85–131
- Touzain P, Balasooriya N, Bandaranayake K, Descolas-Gros C (2010) Vein graphite from the Bogala and Kahatagaha-Kolongaha mines, Sri Lanka: a possible origin. Can Mineral 48(6):1373–1384
- Bandara TMWJ, Thennakoon TMAAB, Gamachchi GGDMG, Bandara LRAK, Pemasiri BMK, Dahanayake U (2022) An electrochemical route to exfoliate vein graphite into graphene with black tea. Mater Chem Phys 289:126450
- 37. Nishshanke GBMMM, Thilakarathna BDKK, Albinsson I, Mellander BE, Bandara TMWJ (2021) Multi-layers of TiO_2 nanoparticles in the photoelectrode and binary iodides in the gel polymer electrolyte based on poly (ethylene oxide) to improve quasi solid-state dye-sensitized solar cells. J Solid State Electrochem 25(2):707–720
- Devadiga D, Selvakumar M, Shetty P, Santosh MS (2021) Dyesensitized solar cell for indoor applications: a mini-review. J Electron Mater 50:3187–3206
- 39. Jiang ML, Wen JJ, Chen ZM, Tsai WH, Lin TC, Chow TJ, Chang YJ (2019) High-performance organic dyes with electron-deficient quinoxalinoid heterocycles for dye-sensitized solar cells under one sun and indoor light. Chemsuschem 12(15):3654–3665
- Bandara TMWJ, Jayasundara WJMJSR, Fernado HDNS, Dissanayake MAKL, De Silva LAA, Albinsson I, Furlani M, Mellander B-E (2015) Efficiency of 10% for quasi-solid state dye-sensitized

solar cells under low light irradiance. J Appl Electrochem 45:289–298

- Chen T, Hu W, Song J, Guai GH, Li CM (2012) Interface functionalization of photoelectrodes with graphene for high performance dye-sensitized solar cells. Adv Func Mater 22(24):5245–5250
- Brown P, Takechi K, Kamat PV (2008) Single-walled carbon nanotube scaffolds for dye-sensitized solar cells. J Phys Chem C 112(12):4776–4782
- 43. Kumari JMKW, Sanjeevadharshini N, Dissanayake MAKL, Senadeera GKR, Thotawatthage CA (2016) The effect of TiO₂ photo anode film thickness on photovoltaic properties of dye-sensitized solar cells. Ceylon J Sci 45(1):33
- 44. Bisquert J, Mora-Seró I (2010) Simulation of steady-state characteristics of dye-sensitized solar cells and the interpretation of the diffusion length. J Phys Chem Lett 1(1):450–456
- 45. Bisquert J, Fabregat-Santiago F, Mora-Sero I, Garcia-Belmonte G, Gimenez S (2009) Electron lifetime in dye-sensitized solar cells: theory and interpretation of measurements. J Phys Chem C 113(40):17278–17290
- 46. Bandara TMWJ, Gunathilake SMS, Nishshanke GBMMM, Dissanayake MAKL, Chaure NB, Olusola OI, Mellander B-E, Furlani M, Albinsson I (2023) Efficiency enhancement and chronophotoelectron generation in dye-sensitized solar cells based on spin-coated TiO₂ nanoparticle multilayer photoanodes and a

ternary iodide gel polymer electrolyte. J Mater Sci Mater Electron 34(28):1969

- Wang YC, Cho CP (2017) Application of TiO2-graphene nanocomposites to photoanode of dye-sensitized solar cell. J Photochem Photobiol A 332:1–9
- Tao E, Ma Z, Yang S, Li Y, Ma D, Xing Z, Li Y (2020) Enhanced electrical conductivity of TiO₂/graphene: the role of introducing Ca²⁺. J Alloy Compd 827:154280
- 49. Das S, Sudhagar P, Kang YS, Choi W (2014) Graphene synthesis and application for solar cells. J Mater Res 29(3):299–319
- Su H, Hu YH (2023) 3D graphene: synthesis, properties, and solar cell applications. Chem Commun. https://doi.org/10.1039/D3CC0 1004J

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

Springer Nature or its licensor (e.g. a society or other partner) holds exclusive rights to this article under a publishing agreement with the author(s) or other rightsholder(s); author self-archiving of the accepted manuscript version of this article is solely governed by the terms of such publishing agreement and applicable law.