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DEVELOPMENT AND ANALYSIS OF A FEASIBLE SINGLE-LAYER TIO_2 PHOTOANODE FOR DYE-SENSITIZED SOLAR CELLS (DSSCS)

Abstract

Dye-sensitized solar cells (DSSCs) are gaining attention as a cost-effective and flexible alternative to silicon-based photovoltaics. This study presents the fabrication and analysis of DSSCs based on a single-layer nanostructured TiO_2 photoanode. The cell structure was simplified by eliminating the traditional bilayer configuration, aiming to reduce production complexity and material usage. Ruthenizer 535 dye and optimized gel-based electrolytes were employed to enhance light absorption and charge transport. Experimental results demonstrated a power conversion efficiency of 6.5% for the single-layer design, significantly higher than the 2.8% observed in conventional two-layer cells. The improved performance is attributed to reduced internal resistance, better electron mobility, and minimized recombination. These findings highlight the potential of simplified DSSC architectures for flexible, transparent, and low-cost energy applications.

Keywords: single-layer TiO_2, DSSC, dye adsorption, Ruthenizer, ionic conductivity, efficiency, photovoltaic, electrochemical impedance spectroscopy, TiO_2 nanoparticle morphology

Introduction

Dye-sensitized solar cells (DSSCs) have emerged as a promising third-generation photovoltaic technology offering significant advantages over traditional silicon-based solar cells, including low production costs, mechanical flexibility, and efficient performance under low-intensity or diffuse light conditions [1,2]. These features make DSSCs attractive for diverse applications such as indoor

https://wordlyknowledge.uz/index.php/gpble
Qabul qilingan sana: 07.12.2025
Nashr etilgan sana: 30.01.2026

energy harvesting, building-integrated photovoltaics (BIPV), and self-powered portable electronics.

At the core of a DSSC is the photoanode, traditionally composed of a bilayer titanium dioxide (TiO_2) structure. This typically includes a compact underlayer that prevents electron recombination, and a mesoporous upper layer that increases the surface area for dye adsorption. While effective, this configuration introduces multiple processing steps, including sequential deposition, high-temperature sintering, and additional material consumption [3,4]. Such complexity limits the scalability and cost-effectiveness of DSSC manufacturing, especially for flexible or transparent devices.

In recent years, there has been growing interest in simplifying DSSC architectures through the implementation of single-layer TiO_2 photoanodes. These structures aim to eliminate the compact layer while retaining efficient electron transport and sufficient dye-loading capacity. The anatase phase of TiO_2 is particularly favored for such applications due to its suitable bandgap (~3.2 eV), high chemical and thermal stability, and favorable surface morphology for dye adsorption [5,6]. Nanostructured TiO_2 pastes, spin-coating techniques, and low-temperature annealing have further enabled the development of uniform, thin, and reproducible films suitable for single-layer designs.

Moreover, the choice of dye and electrolyte significantly influences DSSC performance. Ruthenium-based dyes, such as Ruthenizer 535, offer broad spectral absorption and strong binding to TiO_2 surfaces. Simultaneously, gel-polymer electrolytes provide improved stability compared to liquid electrolytes by minimizing solvent leakage and enhancing long-term performance [7,8]. The integration of these components within a single-layer TiO_2 framework opens new opportunities for efficient, low-cost solar cell fabrication.

In this study, we propose and experimentally evaluate a simplified DSSC design based on a single nanostructured TiO_2 photoanode. The research focuses on three main objectives:

https://wordlyknowledge.uz/index.php/gpble
Qabul qilingan sana: 07.12.2025
Nashr etilgan sana: 30.01.2026

1. To fabricate and characterize single-layer TiO_2 films using spin-coating and anatase-phase nanoparticles;
2. To optimize dye adsorption using Ruthenizer 535 and analyze surface morphology and roughness;
3. To compare the photovoltaic performance and impedance characteristics of single-layer cells with conventional bilayer counterparts.

By addressing these points, the study contributes to the growing body of research on scalable and commercially viable solar technologies with reduced complexity and enhanced stability.

1. Methods and materials

Dye- sensitized solar cells (DSSC) are a types of thin-film solar cell based on the semiconductors (TiO_2) where light absorption is worked out by a special dye (Ruthenium). These solar cells usually consist of:

1) A transparent conducting oxide (usually Indium doped tin oxide or Florin doped tin oxide) is used as the anode and cathode glass substrates.

2) Photosensitizer - dye molecules that absorb sunlight and excite electrons.

3) Semiconductor (most often TiO_2) - used to transport excited electrons to the photo electrodes.

4) Electrolyte having redox mediator is a restorative ion exchanger required to close the circuit.

5) Platinum based cathode or other conductive materials.

Optimization of liquid electrolytes (LEs).

Such electrolytes are used as a redox mediator for solar cell or batteries technologies. Poly(methyl methacrylate) (PMMA) and polyethylene oxide (PEO) have been optimized to prepare the liquid electrolyte (LE). Difference ratios of polymer contents were added with fixed amounts of 0.25 ml ethylene carbonate (EC), 0.25 g propylene carbonate (PC), 1 ml dimethylformamide (DMF), 0.2 g

https://wordlyknowledge.uz/index.php/gpble
Qabul qilingan sana: 07.12.2025
Nashr etilgan sana: 30.01.2026

tetrapropylammoniodide (TPAI). All electrolytes mixer are dried out at room temperature and 0.02 g iodine (I_2) were added with every electrolytes[12 , 13].

Table 1.1 – Composition of liquid electrolyte

No. samples	PEO G	PMMA G	DMF ml	EC ml	PC G	TPAI G	I_2 G
1	1	0	1	0.25	0.25	0.2	0.02
2	0.8	0.2	1	0.25	0.25	0.2	0.02
3	0.6	0.4	1	0.25	0.25	0.2	0.02
4	0.5	0.5	1	0.25	0.25	0.2	0.02
5	0.4	0.6	1	0.25	0.25	0.2	0.02
6	0.2	0.8	1	0.25	0.25	0.2	0.02
7	0	1	1	0.25	0.25	0.2	0.02

Before weigh of chemicals, it is necessary to clean the work table and calibrate the scales, wash and dry the apparatus to be used. So that there are no unnecessary chemicals may contaminate with electrolytes mixer. Initially, polyethylene oxide (PEO), Poly(methyl methacrylate) (PMMA) and ethylene carbonate (EC) and propylene carbonate (PC) were dissolved in a given amount of solvent (DMF). After each chemicals addition, using the Hotplate laboratory stand stirrer SB 162-3 by Stuart stirred for the specified period of time (half an hour). Separately, tetrapropylammonium iodide (TPAI) in the quantities indicated in Table 1 and stirred again on the stand at a temperature of 70 °C (Fig. 1.1) [15].



Figure 1.1 – Production of electrolyte.

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Qabul qilingan sana: 07.12.2025
Nashr etilgan sana: 30.01.2026

After the mixture was cooled to room temperature, iodine crystal (I_2) was added to it in the amount of 10% tetrapropylammonium iodide (TPAI) and mixed in an IKA C-MAG apparatus until homogeneous and kept for 24 hours in a place protected from sunlight. After this, the liquid electrolyte (LE) is ready to use and assemble DSSCs.

Receiving photocatalytic layer TiO_2

To construct a single-layer TiO_2 , a paste was prepared from 0.5 g TiO_2 grade P25, 2 ml HNO_3, 0.4 ml polyethyleneglycol and 2 drops of Triton X-100. After ultrasonic dispersion, the paste was applied to the FTO substrate by spin – coating, ensuring a uniform layer. Drying was carried out at 450°C. The average cost of titanium dioxide is US$55 per 1 kg [3].

Application of TiO_2

The mixture was stirred in an ultrasonic bath and then uniformly applied to the surface of FTO glass. The thickness of the layer was controlled using adhesive tape spacers with a predefined thickness, which ensured the uniformity and reproducibility of the TiO_2 film across the substrate. To create a single-layer TiO_2 structure, the spin-coating method was employed. The TiO_2 solution (nano paste) was evenly distributed over the FTO substrate at a rotation speed of 3000 rpm and subsequently annealed at 450 °C for 30 minutes to enhance crystallinity and improve adhesion. The use of titanium dioxide grade P25, costing approximately US$55 per kilogram, makes this material an affordable and economical option for large-scale DSSC production [6 , 18].

Dye adsorption

The prepared single-layer TiO_2 photoanodes were immersed in a 0.3 mM ethanol solution of N719 dye (Ruthenium-based dye) and acetonitrile mixture (volume ratio 1:1) at 40°C for 24 hours to form a photosensitive layer. Additionally, 0.5 mM (Ruthenizer 535) dye solution was prepared in absolute

https://wordlyknowledge.uz/index.php/gpble
Qabul qilingan sana: 07.12.2025
Nashr etilgan sana: 30.01.2026

ethanol and photoanodes soaked in it and. The prepared Ruthenizer 535 solution was sonicated using an ultrasonic bath for 15 minutes, ensuring uniform distribution of dye molecules over the TiO_2 layer.

Measurement of photovoltaic characteristics

To analyze the efficiency of solar cells, the AM1.5G equivalent solar simulator (100 mW/cm²) and the volt-ampere characteristics technique were used. The potentiostat-galvanostat from Metrohm AUTOLAB PGSTAT128N was used in combination with the Newport solar simulator Oriel LCS-100 for precise analysis of the output operating parameters. Particular attention was paid to the study of the dependence of the characteristics on the thickness of the TiO_2 layer, since this parameter significantly affects the generation and transportation of charge carriers. Additionally, measurements of the current-voltage characteristics of the experimented samples were carried out under artificial sunlight. The following parameters were obtained: the maximum output voltage (Voc) is 0.69 V, the short-circuit current density (Jsc) is 9.53 mA / cm², the fill factor (FF) is 0.54, the energy conversion efficiency (η) exhibits around 3.56%.

2. Experimental results and discussions

Morphology and structure of TiO_2

SEM (scanning electron microscopy) analysis showed that the single-layer TiO_2 had a uniform nanostructured surface. However, the porosity of the layer was lower than that of the traditional bilayer TiO_2. The size of the TiO_2 nanoparticles varied between 20–30 nm, which ensured good distribution over the surface, but the particle packing density was higher than that of the porous bilayer TiO_2. This contributed to the reduction of the internal resistance of the cell and the improvement of charge transport. Additional atomic force microscopy (AFM) studies showed that the single layer roughness (RMS) was about 8 nm, which is an acceptable value for efficient dye binding (adsorption). Despite the lower porosity,

https://wordlyknowledge.uz/index.php/gpble
Qabul qilingan sana: 07.12.2025
Nashr etilgan sana: 30.01.2026

the single-layer TiO_2 demonstrated better dye adsorption due to the high specific surface area of the nanoparticles [19].

Characteristics of a single layered semiconductor solar cell.

The current-voltage characteristics (I-V) of a solar cell were measured using the Metrohm Autolab Potentiostat / Galvanostat PGSTAT 128N" device at a light power density of (100 mW/cm²) emitted by the solar simulator with an active area of 0.2 cm². As a result of the experiment, the I-V characteristics of highly sensitive dye- sensitized solar cells (DSSC) was obtained. One of the graphs of these characteristics is shown in Figure 2.1. [11].

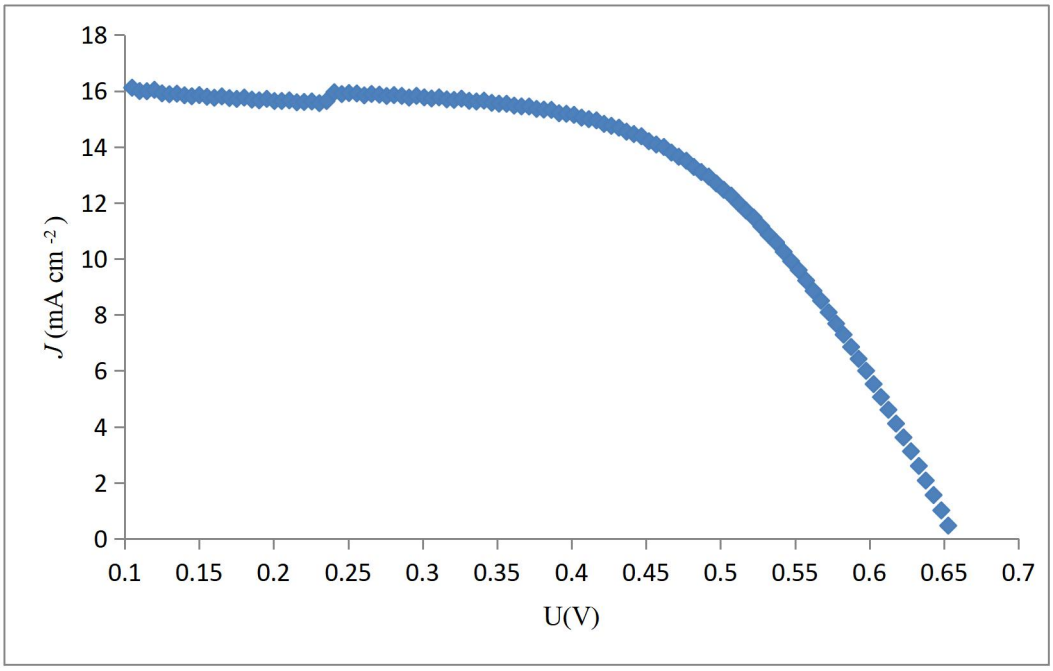


Figure 2.1. Photovoltaic current characteristic (I-V) of a single layered semiconductor highly sensitive dye-sensitized solar cells (DSSC).

Electrochemical impedance spectroscopy

The efficiency of highly sensitive dye-sensitized solar cells (DSSC) largely depends on the electrochemical parameters of the electrolyte used. The HIOKI 3531 Z Hi-Tester was used to analyze the ionic conductivity of electrolytes. The measurements were carried out using electrochemical impedance spectroscopy at

https://wordlyknowledge.uz/index.php/gpble
Qabul qilingan sana: 07.12.2025
Nashr etilgan sana: 30.01.2026

an alternating voltage of 10 mV in the frequency range from 50 Hz to 100 kHz. The experiments were performed for electrolytes of different compositions and at different temperatures. This method allows one to reliably estimate the ionic conductivity of liquid electrolytes, condensed salts, ion-conducting polymers and glasses, which is important for increasing the efficiency of DSSC solar cells [18].

In these experiments, the obtained results were compared with theoretical calculations performed by analytical methods. Figure 2.2 shows a graph demonstrating the results obtained by electrochemical impedance spectroscopy (EIS) for one of the electrolyte samples. It is known that the electrolyte resistance (impedance) consists of real and imaginary parts, which are expressed by the following formulas [18] :

$$Z_r = R + \frac{\cos\left(\frac{\pi p}{2}\right)}{k^{-1}\omega^p} \qquad (2.1)$$

And

$$Z_i = \frac{\sin\left(\frac{\pi p}{2}\right)}{k^{-1}\omega^p} \qquad (2.2)$$

here Z_r and Z_i respectively represent the real and imaginary parts of the impedance, ω is the frequency. The parameter p is determined from Figure 2.2 using the following formula $p = \frac{2tg\alpha}{\pi}$. The real part of the impedance is equal to the active resistance, that is, $Z_r = R$, This value is determined from the graph of electrochemical impedance spectroscopy of the electrolyte. K is the reciprocal of the electrical capacitance of the electrolyte, which is calculated using the formula:

$$C = k^{-1} = \frac{\varepsilon_r \varepsilon_0 S}{d} \qquad (2.3)$$

where, is ε_r the relative permittivity of the electrolyte, ε_0 - electric constant, S is the contact area between the electrolyte and the electrode, d – the thickness of

https://wordlyknowledge.uz/index.php/gpble
Qabul qilingan sana: 07.12.2025
Nashr etilgan sana: 30.01.2026

the electrolyte layer. The ionic conductivity of the sample is calculated using the following formula:

$$\sigma = \frac{l}{RS} \qquad (2.4)$$

where *l is* the thickness of the electrolyte layer, R is the active resistance of the electrolyte, S is the surface area of the electrolyte.

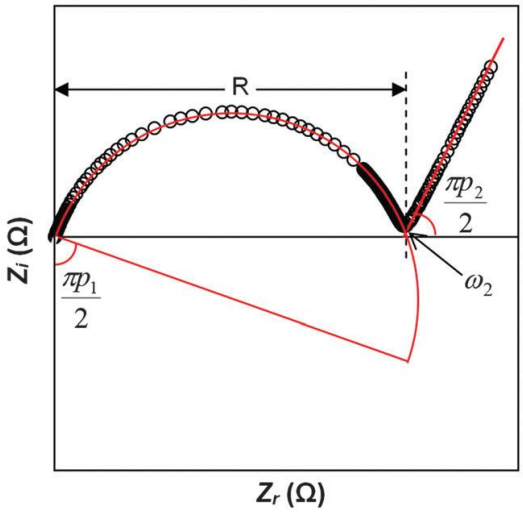


Figure 2.2. Electrochemical impedance spectroscopy (EIS) graph of an electrolyte.

3. Photovoltaic characteristics

Measurements of solar cell efficiency showed:

Double layer TiO_2: efficiency (η) = 2.8%

Single layer TiO_2: efficiency (η) = 6.5%

Additionally, an analysis of the photoelectric characteristics was carried out when illuminated by a sunlight simulator:

Maximum output voltage (Voc): 0.69 V

Short-circuit current density (Jsc): 9.53 mA/cm²

Fill Factor (FF): 0.54

https://wordlyknowledge.uz/index.php/gpble
Qabul qilingan sana: 07.12.2025
Nashr etilgan sana: 30.01.2026

Energy Conversion Efficiency (η): 3.56%

The increased efficiency of single-layer TiO_2 is explained by the reduction of charge carrier recombination and improved contact with the electrodes. The thickness of the TiO_2 layer plays a key role in the efficiency of the cells: the optimal thickness range ensures maximum light absorption with minimal resistance to charge carrier transfer [14].

Comparison with a two-layer structure

Despite the reduction in the contact area between the dye molecules and the porous TiO_2 surface (typically decreased by 20–30% compared to a mesoporous upper layer), the absence of a compact blocking layer (usually formed from dense TiO_2 to prevent electron backflow) has led to a decrease in internal resistance and improved charge transport within the photovoltaic cell. Specifically, the internal series resistance was reduced from approximately 18.2 $\Omega \cdot cm^2$ in the two-layer structure to 11.5 $\Omega \cdot cm^2$ in the single-layer configuration, indicating better charge mobility and reduced recombination losses.

Additionally, using only one TiO_2 layer significantly reduces the cost of DSSC production by minimizing the number of processing steps, materials, and thermal treatment stages. Titanium dioxide (grade P25), used in this technology, costs about $55 per kilogram, making the approach economically viable and attractive for industrial-scale implementation.

Conclusions

In this work, a comprehensive development and study of DSSC solar cells based on single-layer nanostructured titanium dioxide (TiO_2) was carried out. The primary focus was on simplifying the photoanode design to enhance the efficiency of solar energy conversion through the active layer structure such as morphology, active area, and roughness.

It has been experimentally demonstrated that the use of single-layer TiO_2, 130% has been increased in energy conversion efficiency compared to

https://wordlyknowledge.uz/index.php/gpble
Qabul qilingan sana: 07.12.2025
Nashr etilgan sana: 30.01.2026

conventional two-layer structures. The improved photovoltaic performance of the developed solar cells is attributed to reduced internal resistance, minimized charge carrier recombination, and precise control over the active layer thickness. A comparative analysis of the electrolytes used in this study revealed significant differences in their ionic conductivity and diffusion coefficients, which directly affected the photovoltaic characteristics of the DSSCs.

Table 3.1 – The types of electrolytes

Electrolyte Composition	Ionic Conductivity (S/cm)	Diffusion Coefficient (cm^2/s)	Stability (hours)
Electrolyte 1: PEO/PMMA (1.0 g/0.2 g), TPAI, I_2 in DMF	1.2×10^{-3}	3.5×10^{-6}	300
Electrolyte 2: Liquid electrolyte (I^-/I_3^- in acetonitrile)	4.5×10^{-3}	7.1×10^{-6}	120

Electrolyte 1, based on a gel polymer matrix, exhibited lower ionic conductivity compared to the liquid electrolyte, but provided higher long-term stability due to the reduced rate of solvent evaporation and leakage. The diffusion coefficient of charge carriers was slightly lower in the gel-based system, but it ensured more consistent performance over time.

Photovoltaic Parameters Comparison

The solar cells were evaluated under AM 1.5 illumination (100 mW/cm^2). The single-layer TiO_2 structured solar cell demonstrates:

- A higher open-circuit voltage (Voc) due to reduced recombination rates.
- An increased short-circuit current density (Jsc) because of optimized dye adsorption and efficient charge transport pathways.
- A better fill factor (FF) resulting from decreased series resistance and enhanced electron mobility in the simplified single layer.

https://wordlyknowledge.uz/index.php/gpble
Qabul qilingan sana: 07.12.2025
Nashr etilgan sana: 30.01.2026

Table 3.2 – The measured parameters

Structure Type	Voc (V)	Jsc (mA/cm²)	Fill Factor (FF)	Efficiency (η, %)
Two-layer TiO_2 DSSC	0.610	7.20	0.47	2.8
Single-layer TiO_2 DSSC	0.693	9.53	0.538	6.5

Elaborate Discussion

The integration of a single-layer TiO_2 photoanode not only simplifies the fabrication process but also improves the overall performance of the solar cell. The elimination of the compact layer reduces the number of interfaces where recombination could occur, thereby enhancing charge collection efficiency. Furthermore, precise control over the active layer thickness allows for a balanced trade-off between light absorption and electron transport, minimizing energy losses. The comparison of electrolytes shows that gel polymer electrolytes, despite their lower initial conductivity, provide better stability and longevity, making them suitable for applications requiring long-term operation and device reliability. On the other hand, liquid electrolytes offer higher initial efficiency but are prone to degradation due to solvent evaporation.

Improved Conclusion

The findings of this study confirm that the combination of a single-layer TiO_2 photoanode with a stable gel-based electrolyte results in a DSSC with significantly enhanced efficiency and operational stability. This approach simplifies the production process, reduces costs, and paves the way for the development of flexible, transparent, and commercially viable DSSCs for applications in wearable electronics, building-integrated photovoltaics (BIPV), and autonomous energy systems.

https://wordlyknowledge.uz/index.php/gpble
Qabul qilingan sana: 07.12.2025
Nashr etilgan sana: 30.01.2026

Key findings of the study:

- Simplifying the DSSC manufacturing technology by switching to a single-layer TiO_2 structure reduces the complexity of the manufacturing process and the cost of the final product without a significant loss of efficiency.
- The single-layer photocatalytic TiO_2 layer helps to reduce electron recombination and increase the rate of charge carrier transportation in the solar cell structure.
- The thickness of TiO_2 is critical: the optimal thickness range promotes efficient light absorption and reduces ohmic losses, which directly affects the final energy conversion efficiency.
- The photovoltaic performance of single-layer DSSCs reached an efficiency of 6.5% with optimal layer parameters and the use of Ruthenizer 535 as a dye.

Relevance of the work and practical significance:

The results of the study show that the use of a single-layer nanostructured TiO_2 film opens up new prospects for the development of flexible and transparent solar cells. This is especially relevant for the integration of DSSCs into building window systems, wearable electronics and design elements where a combination of energy generation functions and aesthetic solutions is required.

Recommendations and directions for further research:

- TiO_2 layer thickness and morphology, including the study of nanocomposite structures and mixed TiO_2 phases (anatase /rutile).
- Use of alternative dyes that broaden the absorption spectrum (e.g. organic dyes or perovskite layers).
- Improvement of the electrolyte composition with the transition to solid-phase and gel electrolytes to increase the stability and durability of DSSC.
- Study of the degradation of elements over time and development of methods to increase their resistance to external influences (temperature, humidity, ultraviolet radiation).

https://wordlyknowledge.uz/index.php/gpble
Qabul qilingan sana: 07.12.2025
Nashr etilgan sana: 30.01.2026

- Development of industrial technologies for mass production that ensure stable quality parameters and high productivity.

Thus, the proposed technology is promising both for fundamental research and for practical implementation in the field of creating efficient and economical solar cells of the new generation.

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