УДК 621.383.51 EDN BXETIC

Изготовление и оптимизация однослойных TiO_2-фотоанодов для сенсибилизированных красителем солнечных элементов

С. Шарипбаев[1*], А. Эргашов[1], Р. Турсунбоев[2]

[1]Наманганский государственный технический университет, 160115, Наманган, Узбекистан
[2]Школа № 28, Касансайский район, Наманганская область, 160300, Узбекистан

*E-mail: sharipbayev1999@mail.ru

Аннотация. Представлен экспериментально обоснованный подход к формированию однослойного мезопористого TiO_2-фотоанода для сенсибилизированных красителем солнечных элементов (DSSC). Рассмотрены приготовление пасты на основе P25, ультразвуковое диспергирование, контролируемое нанесение покрытия на проводящее FTO-стекло, термическая обработка, сенсибилизация красителем Ruthenizer 535 и применение гель-полимерного электролита PEO/PMMA. Показано, что фотоэлектрические характеристики определяются совместным влиянием размера частиц, пористости, толщины слоя, межчастичных контактов, загрузки красителя и рекомбинационных процессов. Наиболее благоприятный морфологический интервал соответствует среднему размеру частиц 15-25 нм, пористости 50-60 % и толщине активного слоя 10-14 мкм. Паста TiO_2 наносилась на FTO контролируемым методом, близким к doctor-blade, после чего образцы спекались при 450 °C в течение 30 мин. При оптимизированных условиях получена эффективность преобразования энергии около 6,47 % и плотность тока короткого замыкания около 16,5 мА/см². Результаты SEM, AFM, XRD, BET, импедансных и фотоэлектрических измерений подтверждают, что согласованное управление морфологией повышает воспроизводимость. Однослойная структура характеризуется более однородным распределением наночастиц, улучшенной связностью пор и меньшей агломерацией по сравнению с двухслойной архитектурой. Полученные результаты подтверждают перспективность технологически простой однослойной архитектуры DSSC.

Ключевые слова: DSSC, TiO_2-фотоанод, мезопористая структура, P25, гель-полимерный электролит, транспорт электронов.

Для цитирования: Шарипбаев, С. Изготовление и оптимизация однослойных TiO_2-фотоанодов для сенсибилизированных красителем солнечных элементов / С. Шарипбаев, А. Эргашов, Р. Турсунбоев // Модернизация, Инновации, Прогресс (MIP ENGINEERING-VII-2026): материалы VII Всероссийской (национальной) научной конференции (Красноярск, 11–12 сентября 2026 г.). – Красноярск: Красноярский краевой Дом науки и техники Российского Союза научных и инженерных общественных объединений, 2026. – Т. 20. – С. 373-377. – EDN: BXETIC.

Fabrication and optimization of single-layer TiO_2 photoanodes for dye-sensitized solar cells

S. Sharipbaev[1*], A. Ergashov[1], R. Tursunboev[2]

[1]Namangan State Technical University, 160115, Namangan, Uzbekistan
[2]School No. 28, Kasansay Region, Namangan region, 160300, Uzbekistan

*E-mail: sharipbayev1999@mail.ru

Abstract. An experimentally grounded approach to forming a single-layer mesoporous TiO_2 photoanode for dye-sensitized solar cells (DSSCs) is presented. The procedure includes preparation of a P25-based TiO_2 paste, ultrasonic dispersion, controlled coating of conductive FTO glass, thermal treatment, sensitization with Ruthenizer 535 dye, and use of a PEO/PMMA gel-polymer electrolyte. Photovoltaic performance is shown to depend on the combined effects of particle size, porosity, film thickness, interparticle connectivity, dye loading, and recombination. The most favorable morphological interval corresponds to an average particle size of 15-25 nm, porosity of 50-60%, and an active-layer thickness of 10-14 μm. The TiO_2 paste was deposited on FTO by a controlled spreading procedure analogous to the doctor-blade method, followed by sintering at 450 °C for 30 min. Under optimized device conditions, a power conversion efficiency of approximately 6.47% and a short-circuit current density of about 16.5 mA cm^{-2} were obtained. SEM, AFM, XRD, BET, impedance, and photoelectrical results confirm that coordinated morphology control improves reproducibility and supports the use of a technologically simple single-layer DSSC architecture.

Keywords: DSSC, TiO_2 photoanode, mesoporous structure, P25, gel-polymer electrolyte, electron transport.

For citation: Sharipbaev, S. Fabrication and optimization of single-layer TiO_2 photoanodes for dye-sensitized solar cells / S. Sharipbaev, A. Ergashov, R. Tursunboev // Modernization, Innovations, Progress (MIP ENGINEERING-VII-2026): Proceedings of the VII All-Russian (National) Scientific Conference (Krasnoyarsk, September 11–12, 2026). – Krasnoyarsk: Krasnoyarsk Regional Science and Technology City Hall of the Russian Union of Scientific and Engineering Public Associations, 2026. – Vol. 20. – P. 373-377. – EDN: BXETIC.

1. Introduction

Dye-sensitized solar cells are attractive third-generation photovoltaic devices because they combine a comparatively simple fabrication route with the possibility of using low-cost materials and transparent conducting substrates. In a conventional n-type DSSC, the TiO_2 photoanode provides a large internal surface for dye adsorption, accepts electrons injected from the excited sensitizer, transports these electrons toward the FTO current collector, and forms the interface with the redox electrolyte. Consequently, the morphology and structural quality of the TiO_2 layer directly influence light harvesting, charge transport, recombination, and final photovoltaic parameters [1, 2]. Related mathematical modeling of processes in dye-sensitized photocells has also been reported [3].

2. Problem Statement and Research Objective

The study focuses on a technologically simple single-layer mesoporous TiO_2 photoanode and on the relationship between its morphology and DSSC performance. The objective is to identify a rational range of particle size, porosity, and active-layer thickness that balances dye adsorption, electron diffusion, and recombination while maintaining a reproducible fabrication sequence. Particular attention is given to avoiding unnecessary multilayer interfaces that can increase resistance or contribute to delamination.

3. Materials and Methods

3.1. Preparation of the TiO_2 photoanode

FTO substrates were cleaned with ethanol and dried. A TiO_2 paste was prepared from 0.5 g of P25 nanoparticles using nitric acid, polyethylene glycol, and Triton X-100. Nitric acid was used to control the chemical environment and facilitate particle dispersion, polyethylene glycol acted as a binder and pore-forming component, and Triton X-100 improved wetting and suspension homogeneity. The mixture was homogenized and subjected to ultrasonic treatment for 30 min. Reducing particle agglomeration promotes a more uniform mesoporous network and improves the continuity of electron-transport pathways.

The TiO_2 paste was deposited on the conducting side of the FTO glass by a controlled spreading procedure analogous to the doctor-blade method. Spacers were used to define the active area and limit film thickness. After coating, the samples were sintered at 450 °C for 30 min. Thermal

treatment removes organic components, promotes neck formation between TiO_2 nanoparticles, decreases intergranular resistance, and improves adhesion of the oxide layer to FTO. Natural cooling to room temperature was used to reduce thermal stress and the probability of microcrack formation.

3.2. Dye sensitization and gel-polymer electrolyte

Ruthenizer 535 dye was dissolved in ethanol. The sintered TiO_2 photoanodes were treated ultrasonically to improve dye penetration and then kept in the dye solution in the dark for 24 h. This procedure promotes sensitizer adsorption throughout the mesoporous network. A polymer gel electrolyte based on polyethylene oxide (PEO), polymethyl methacrylate (PMMA), ethylene carbonate, propylene carbonate, dimethylformamide, tetrapropylammonium iodide, and iodine was prepared. The PEO/PMMA matrix combines ion transport with improved mechanical stability and reduces leakage compared with a fully liquid electrolyte [4].

3.3. Structural and photoelectrical characterization

The photoanodes and assembled cells were evaluated using scanning electron microscopy (SEM), atomic force microscopy (AFM), X-ray diffraction (XRD), Brunauer–Emmett–Teller (BET) surface-area analysis, electrochemical impedance methods, and photoelectrical measurements. These techniques were used to relate particle size, porosity, film thickness, phase composition, interfacial resistance, and charge-transfer behavior to the photovoltaic response [5].

4. Results and Discussion

4.1. Morphological optimization

Morphological optimization was found to be a compromise. Small TiO_2 nanoparticles increase the specific surface area and therefore improve dye loading. The BET specific surface area decreased from 132 $m^2\ g^{-1}$ for 10 nm particles to 47 $m^2\ g^{-1}$ for 30 nm particles, while the corresponding dye loading also decreased. At the same time, excessively small particles increase the number of grain boundaries and localized surface states, which may slow electron diffusion and increase recombination. Larger particles can improve connectivity and light scattering but reduce the available adsorption area. The most favorable interval identified in the study corresponds to an average particle size of approximately 15-25 nm.

Porosity has a similarly dual role. A sufficiently open pore network facilitates electrolyte penetration and increases the effective TiO_2/dye/electrolyte contact area, whereas very high porosity may reduce electronic-network connectivity. An optimal porosity range of about 50-60% was

identified. Film thickness must also be coordinated with the electron diffusion length. Increasing thickness initially improves light absorption and dye loading, but excessive transport distance increases the probability of recombination. An active-layer thickness of roughly 10-14 μm was therefore identified as a rational design range [2].

4.2. Photovoltaic and structural performance

The photovoltaic measurements show that the polymer-matrix composition strongly affects device operation. Among the tested formulations, the best power conversion efficiency was approximately 6.47%, while the maximum short-circuit current density reached about 16.5 mA cm^{-2}. The high current density is consistent with enhanced light utilization, sufficient dye loading, and improved charge collection in the optimized photoanode/electrolyte system. The open-circuit voltage and fill factor varied more moderately, indicating that recombination kinetics and interfacial resistance remain important even when current generation is improved.

SEM observations showed that the single-layer TiO_2 photoanode had a more homogeneous nanoparticle distribution, better pore connectivity, and lower agglomeration than the compared double-layer architecture. The more uniform single-layer structure provides continuous electron-transport routes and reduces localized structural defects. XRD data indicated the predominance of anatase after thermal treatment, which is advantageous for DSSC electron transport. The combined SEM, AFM, XRD, BET, impedance, and photoelectrical analyses confirm that the efficiency gain is associated with coordinated morphology control rather than with a single processing variable.

From a practical viewpoint, the proposed fabrication sequence does not require a complicated multilayer architecture. The principal technological requirements are homogeneous dispersion of the TiO_2 paste, controlled coating, reproducible thermal treatment, sufficient dye-sensitization time, and a stable redox electrolyte. A carefully engineered single-layer mesoporous TiO_2 photoanode can therefore provide efficient light harvesting and electron collection while avoiding additional interlayer interfaces that may contribute to resistance and delamination.

5. Conclusions

The study establishes a direct relationship between TiO_2 morphology, charge-transport conditions, and DSSC photovoltaic performance. A particle size of 15-25 nm, porosity of 50-60%, and an active-layer thickness of 10-14 μm form a rational morphological window for balancing dye adsorption, electron diffusion, and recombination. The P25-based single-layer fabrication route, combined with ultrasonic dispersion, sintering at 450 °C, Ruthenizer 535 sensitization, and a

PEO/PMMA gel-polymer electrolyte, provides a reproducible technological basis for efficient and mechanically stable DSSCs. Under optimized conditions, the reported conversion efficiency was approximately 6.47% and the short-circuit current density was about 16.5 mA cm^{-2}.

References

1. Performance improvement of dye-sensitized solar cells with pressed TiO2 nanoparticles layer / T. Ch. Wu, W. M. Huang, T. H. Meen, J. K. Tsai // Coatings. – 2023. – Vol. 13, No. 5. – P. 907. – https://doi.org/10.3390/coatings13050907. – EDN: QJFTED.
2. Optimization thickness of photoanode layer and membrane as electrolyte trapping medium for improvement dye-sensitized solar cell performance / N. Kusumawati, P. Setiarso, S. Muslim [et al.] // Science and Technology Indonesia. – 2024. – Vol. 9, No. 1. – P. 7-16. – https://doi.org/10.26554/sti.2024.9.1.7-16. – EDN: FWCPUW.
3. Sharibaev, N. Mathematical modeling of processes in dye-sensitized photocell / N. Sharibaev, A. Ergashov // Journal of Physics: Conference Series: III International Conference on Metrological Support of Innovative Technologies (ICMSIT-III-2022), Krasnoyarsk, 03-05 march 2022, Vol. 2373. – IOP Publishing Ltd, 2022. – P. 72044. – https://doi.org/10.1088/1742-6596/2373/7/072044. – EDN: IVPCTI.
4. Electrocatalytic and structural properties and computational calculation of PAN-EC-PC-TPAI-I2gel polymer electrolytes for dye sensitized solar cell application / F. I. Chowdhury, J. Islam, A. K. Arof [et al.] // RSC Advances. – 2021. – Vol. 11, No. 37. – P. 22937-22950. – https://doi.org/10.1039/d1ra01983j. – EDN: MEEISC.
5. Kim, G.O., Dynamic response of charge transfer and recombination at various electrodes in dye-sensitized solar cells investigated using intensity modulated photocurrent and photovoltage spectroscopy / G.O. Kim, R.S. Ryu // Bulletin of the Korean Chemical Society. – 2012. – Vol. 33, No. 2. – P. 469-472. – https://doi.org/10.5012/bkcs.2012.33.2.469.