RESEARCH ARTICLE OPEN ACCESS

Nanomaterials for photoelectrodes in dye sensitized solar cells-a Review

Reshmi Krishnan S.
Department of Electrical and Electronics Engineering, Sree Chitra Thirunal College of Engineering, Thiruvananthapuram, Kerala, India 695018.

ABSTRACT
Dye-sensitized solar cells (DSSCs) are the representative of third generation photovoltaicdevices due to its low cost, easy fabrication, and relatively high energy conversion efficiency. Still, there is a lot of scope for the replacement of current DSSC materials due to their high cost, less abundance, and long-term stability. Thispaper summarizes the recent progress in DSSC technology for improving efficiency, focusing on the active layer in the photoanode,with a part of the DSSC consisting of dyes and a TiO_2film layer. The application of these nanostructured photoanode materials and their impact on the device efficiency has been described in detail.
Keywords: dye sensitized solar cells, fill factor, photoelectrode,power conversion efficiency

Date of Submission: 22-01-2021 Date of Acceptance: 06-02-2021

I. INTRODUCTION

Fossil fuels (coal, oil, and natural gas) form the major energy source for meeting current humanneeds, yet cause a range of serious environmental issues. Moreover, the ever-growing consumptionrate outpaces their regeneration rate, endangering the exhaustion of fossil fuels on earth. Among all new competing energy sources (biomass, solar, wind, hydroelectricity, geothermal energy, and nuclear energy), solar energy is considered to be the most abundant, renewable, and environment-friendly energy form.

Dye-sensitized solar cells (DSSCs) have arisen as a technicallyand economically credible alternative to the p-njunction photovoltaic devices Furthermore, DSSCswork better even during darker conditions, such as in the dawn anddusk or in cloudy weather. Such capability of effectively utilizingdiffused light makes DSSCs an excellent choice for indoor applicationslike windows and sunroof [1].

DSSC consists of a mesoporous nanocrystalline n-type semiconductor (typically TiO_2)sensitized with a dye, deposited onto an anode and immersed in redox active electrolyte (generallytriiodide/iodide), completed by a counter-electrode (cathode) [2]. Upon illumination, dye moleculesanchored onto the TiO_2 surface absorb incoming photons, allowing the photoinduced electron-transferfrom their excited state into the TiO_2 conduction band. Then, the electrons are transferred to the counterelectrode, thus creating a current. The redox electrolyte reduces the oxidized dye molecules back totheir ground state to enable continuous electron production. Even if power conversion efficiencies(PCEs) above 13% have been reached for liquid-electrolyte DSSCs [3,4] improvements are stillrequired in order to be commercially viable.

Dye-sensitized solar cell (DSSC) offers an efficient and easily implemented technology for future energy supply. Compared to conventional silicon solar cells, it provides comparable power conversion efficiency (PCE) at low material and manufacturing costs. DSSC materials such as titanium oxide (TiO_2) are inexpensive, abundant and innocuous to the environment. Since DSSC materials are less prone to contamination and processable at ambient temperature, a roll-to-roll process could be utilized to print DSSCs on the mass production line. The main objective of this review article is to provide an overview of TiO_2-based photoanode layer used in dye-sensitized solar cells (DSSCs).

II. THE STRUCTURE AND OPERATION PRINCIPLE

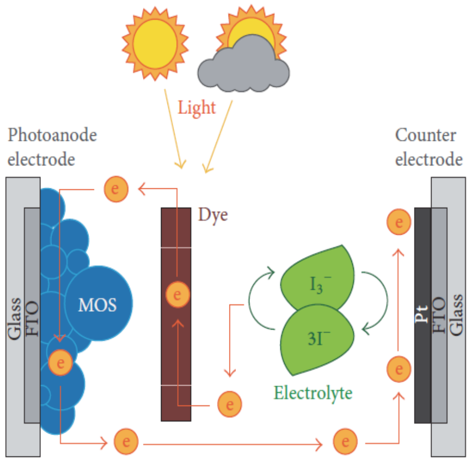

Figure 1: Schematic representation of a DSSC device.

The device is comprised of fourcomponents only:
(i) Nanostructured n-type semiconductor (wide band gap metal oxide) coated over transparent conducting substrate (TCO (ITO [6] or FTO [7]))
(ii) Visible-light absorber dye (several organic dye can be used, such as N3 [8], N719 [9], N749 [10] (the so called black dye), K8 [11], K19 [12], CYC-B11 [13], and C101 [5]
(iii) Electrolyte containing redox couple (typically, I^-/I_3^-) in an organic solvent to collect electrons at the counter electrode and effecting dye-regenerating; and [14, 15]
(iv) Counter electrode (TCO coated with a platinum layer or other suitable catalyst)
The working of DSSCs is a step-by-step sequential phenomenon, carried out by different layers as shown below:
• The dye or the sensitizer is the photoactive material of DSSC and is responsible for the production of energy on exposure to light.
• The dye absorbs the incoming light (sunlight), that is, the photons that cause the excitation of electron from HOMO to LUMO in the dye.
• After that, these excited electrons are then transported into the conduction band of TiO_2 (a white pigment commonly found in white paint) and thus the anode of DSSCs. Meanwhile, the dye rapidly reduced by taking an electron from the electrolyte. The rare-earth elements are one of the most potential dopants for TiO_2 explored to date in order to modify and improve the functionality of TiO_2 in DSSCs.

When the sunlight strikes the solar cell, dye sensitizers on the surface of TiO_2 film get excited and the electrons in turn get injected into the conduction band of TiO_2. Within the TiO_2 film, the injected electrons diffuse all the way through the mesoporous film to the anode and are utilized to do useful work at the external load. Finally, to complete the cycle, these electrons are collected by the electrolyte at counter electrode which in turn are absorbed to regenerate the dye sensitizer. The overall performance of the DSSC can be evaluated basedon sunlight-to-electric power conversion efficiency (PCE or η) and fill factor

$$FF = \frac{V_{max}J_{max}}{V_{oc}J_{sc}} \quad (1)$$

$$\eta = \frac{V_{oc}J_{sc}\,FF}{P_{in}} \times 100\% \quad (2)$$

where J_{sc} is theshort-circuitcurrentdensity(mAcm^{-2}), V_{oc}, the open-circuit voltage(V), FF the fill factor and P_{in} the incidentlightpower. J_{max} and V_{max}corresponds tocurrentandvoltagevalues,respectively, where themaximumpoweroutputisgiveninthe J–V curve.The photovoltage (V_{oc}) is determined by the potential difference between Fermi-level of electrons in the TiO_2 film and redox potential of electrolyte. Similarly, the photocurrent (J_{sc}) is determined based on theincident light harvest efficiency (LHE), charge injection and collection efficiencies. The fill factor (FF) represents the ratio of the actual maximum obtainable power to the product of the open circuit voltage (V_{oc}) and short circuit current (J_{sc}).

In general, the overall conversionefficiency of dye-sensitized solar cells is tested under standard irradiation conditions (100 mW/cm^2, AM 1.5). The I-V curve to show the cell performance is shown in Fig2.

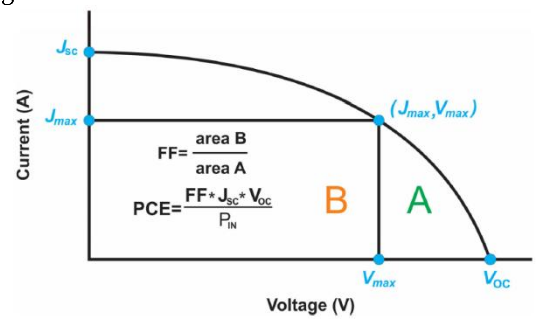

Fig. 2 I–V curve to evaluate the cells performance

Under standard test conditions, the device efficiency can be maximized through optimizing each of these three parameters (V_{oc}, J_{sc}, and FF). For instance, high open-circuit potential can be obtained by using C_o(II/III) redox couple which has more positive redox potential and therefore increases the potential difference. Likewise, the short-circuit current can be enhanced by using panchromatic dye sensitizers which can absorb broad sunlight covering visible to the near-infrared range in solar spectrum. The fill factor is yet anotherimportant parameter that reflects the quality of solar cells. Increasing the shunt resistance and decreasing the series resistance as well as reducing the overvoltage for diffusion and electron transfer will lead to a higher FF value, thus resulting in greater efficiency and pushing theoutput power of the solar cell closer towards its theoretical maximum. In fact, these parameters are highly dependent on material properties and physical processes within the device. Therefore, theoretical models that can capture the characteristics of physical process and materials properties are critical to optimize various operation parameters andcell configurations.

III. EXPERIMENTAL FINDINGS

Mathew et al.[16] prepared TiO_2 nanoparticle based photoanodes sensitized with molecularly engineered porphyrin based sensitizers (SM315) which exhibits an efficiency of 13% .The sensitizer exhibits enhanced visible and long wavelength absorbance combined with excellent electrolyte compatibility.

All the record efficiencies reported so far uses TiO_2 nanoparticles as the semiconductor layer and the enhancement in the efficiencies are mainly attributed to the performance of the dye. The one-dimensional nanostructure provides higher light scattering compared to nanoparticles. Although one dimensional photoanodes show great promise in terms of the electron transport and light scattering, the maximum efficiency reported so far using nanotube electrodes is 9.5% [17,18].The major drawback of the one-dimensional photoelectrodes is the low surface area available for the adsorption of dye molecules.

Varghese et al. [19] found that dye-sensitized solar cells consist of a random network of titania nanoparticles that serve both as a high-surface-area support for dye molecules and as an electron-transporting medium. Despite achieving high power conversion efficiencies, their performance is limited by electron trapping in the nanoparticle film. Electron diffusion lengths can be increased by transporting charge through highly ordered nanostructures such as titania nanotube arrays. Although titania nanotube array films have been shown to enhance the efficiencies of both charge collection and light harvesting, it has not been possible to grow them on transparent conducting oxide glass with the lengths needed for high-efficiency device applications (tens of micrometres).

Microflowers, Nanowires, Fusiforms, Nanopetals, Nanochains, 3D dendrites, Hollow Urchin and Inverse opal [20-27] are some of the other potential TiO_2 nanostructures that have been reported so far

Tong et al.[28] conducted preliminary experiments of introducing intermediate band into the TiO_2-based photoanodes of DSSCs by doping nominal trace amount W^{6+} ions. The enhancement of J_{sc} and conversion efficiency might partially be attributed to the formation of intermediate band in the bandgap of TiO_2. In addition, the electron transport and electron lifetime were improved after doping W^{6+} in TiO_2, which also benefited the enhancement of J_{sc} and conversion efficiency. A notable improvement of the device performance was obtained when N-type W-doped TiO_2 films were applied as the photoanode of DSSCs. The short-circuit current density (J_{sc}) increased from 12.40 mA cm^{-2} to 15.10 mA cm^{-2}, and the conversion efficiency increased from 6.64 to 7.42% when nominal 50 ppm W-doped TiO_2 was adopted.

Latini et al. [29]prepared solid solutions of scandium in anatase as semiconductor material for DSSC photoanodes by the controlled hydrolysis of titanium (IV) isopropoxide and scandium (III) isopropoxide in hydroalcoholic medium. The final powder was constituted by mesoporous anatase beads doped with Sc. Several DSSCs with photoanodes at different Sc doping were tested both under solar simulator and in the dark. The maximum efficiency of 9.6% was found at 0.2 at. % of Sc in anatase that is 6.7% higher with respect to the DSSCs with pure anatase. In conclusion, the whole picture emerging from the experimental results of the present work indicates that the DSSC performances can be improved through a careful dosage of Sc in anatase together with a strict control of each step of the cell assembly by bothering about the chemistry of materials.

Bakhshayesh et al.[30] reported a facile deposition of uniform photoanode electrodes by a novel anatase-stabilised gel for dye-sensitised solar cells (DSSCs) applications. Highly crystalline anatase–TiO_2 phase is stabilised by indium nitrate at 500^0C. The anatase-stabilised DSSC has higher power conversion efficiency of 7.48% than that of unstabilised cell (6.37%).

Subramanian A et al. [31] investigated the use ofTitanium nanotubes doped with boron as the photoelectrode for dye-sensitized solar cells. The materials were characterized by SEM, XRD, and UV–vis spectroscopy and their photoconversion efficiencies were evaluated. The chemical compositions of TiO_2 nanotubes (TNA) and boron doped TNA (B-TNA) were identified by the energy dispersive X-ray spectroscopy (EDS). The boron-doped TiO_2 nanotube arrays showed an enhanced performance with a photocurrent density of 7.85±0.20mA/cm^2 and an overall conversion efficiency (η) of 3.44±0.10%.

Song J et al.[32] demonstrated a strategy to improve utilization of photogenerated charge in dye-sensitized solar cells (DSSCs) with fluorine-doped TiO_2 hollow spheres as the scattering layer, which improves the fill factor from 69.4% to 74.1% and in turn results in an overall efficiency of photoanode increased by 13% (from 5.62% to 6.31%) in comparison with the control device using undoped TiO_2 hollow spheres. It is proposed that the fluorine-doping improves the charge transfer and inhibition of charge recombination to enhance the utilization of the photogenerated charge in the photoanode.

Tabari-SaadiYet al. [33] fabricated different structures of TiO_2 photoelectrodes with various arrangement modes of the layers. TiO_2 nanoparticles, synthesized by stabilizing agent free non-hydrolytic sol–gel method, are employed as the under layer, whereas carbon-doped TiO_2 hollow spheres, prepared by hydrothermally grown carbon template, are used as the scattering layer of solar cells. The nanoparticles (22 nm) have anatase structure, while 300–700 nm hollow spheres show mixtures of anatase and rutile phases. X-ray photoelectron spectroscopy confirms that carbon is doped into TiO_2 hollow spheres, resulting in a decrease in band gap energy in the range 2.96–3.13 eV compared with 3.04 eV band gap energy for the nanoparticles.

Dye-sensitized solar cells (DSSCs) were fabricated by Lin J et al.[34] by incorporating transparent electrodes of ordered free-standing TiO_2 nanotube (TNT) arrays with both ends open transferred onto fluorine-doped tin oxide (FTO) conductive glass. The high-quality TiO_2 membranes used here were obtained by a self-detaching technique, with the superiorities of facile but reliable procedures. Afterwards, these TNT membranes can be easily transferred to FTO glass substrates by TiO_2 nanoparticle paste without any crack. This showed an enhanced solar energy conversion efficiency as high as 5.32% of 24-μm-thick TiO_2 nanotube membranes without further treatments. These results reveal that by facilitating high-quality membrane synthesis, this kind of DSSCs assembly with optimized tube configuration can have a fascinating future.

Song CBet al.[35] fabricated DSSCs based on the novel G-TiO_2NPs/TiO_2 NTs bilayer structure photoanodes by a direct mechanical mixing and spin-coating method. The results showed that the incorporation of 0.1 wt% graphene into the TiO_2 pastes increased the total solar cell efficiency by 44% due to the enhanced electron transferring. However, higher graphene loading beyond the optimal concentration can cause the decrease of the efficiency due to the light shielding of graphene. This study will provide new insight into the fabrication and structural design of highly efficient DSSCs.

Patle LB et al.[36] prepared dip coated TiO_2 semiconductor meet enough porosity for the application of DSSC. The films deposited were prepared by 10 cycles and observed thickness about 8-9 µm. The thickness could be increased by increasing cycles but when dried the coated TiO_2 film gets peeled off from the substrate. Even increasing the Cu concentration after 3% the TiO_2 film gets detached from the substrate. This shows that the adhesion of film is very poor for more than 10 cycles as well as Cu concentration more than 3%. Further the investigation has shown the effect of Cu doping in TiO_2 semiconductor reduces the band gap of TiO_2up to 10%. This decrease in band gap energy of TiO_2 semiconductor corresponds to increase in open circuit voltage of the DSSC. On the other hand,with increase in Cu concentration the short circuit current and photon to current conversion efficiency of the DSSC decreases.

Mao X [37] synthesized photoanode of 3.4 nm-sized SnO_2 nanocrystals (NCs) via the hot-bubbling method. The optimal percentage of the doped SnO_2 NCs was found at ~7.5% (SnO_2/TiO_2, *w*/*w*), and the fabricated DSSC delivers a power conversion efficiency up to 6.7%, which is 1.52 times of the P25 based DSSCs.

Llanos J et al. [38] prepared $Y_{1.86}Eu_{0.14}WO_6$ phosphors using a solid-state reaction method. Their optical properties were analysed, and they were mixed with TiO_2, sintered, and used as a photoelectrode (PE) in dye-sensitized solar cells (DSSCs). The as-prepared photoelectrode was characterized by photoluminescence spectroscopy, diffuse reflectance, electrochemical impedance spectroscopy (EIS) and X-ray diffraction. The photoelectric conversion efficiency of the DSSC with TiO_2:$Y_{1.86}Eu_{0.14}WO_6$ (100:2.5) was 25.8% higher than that of a DSCC using pure TiO_2 as PE. This high efficiency is due to the ability of the luminescent material to convert ultraviolet radiation from the sun to visible radiation, thus improving the solar light harvesting of the DSSC. The photo-conversion efficiency of dye sensitized solar cells fabricated using different photoanode materials are tabulated in Table 1.

Table1: Performance of dye sensitized solar cell using various photoanode materials

Photoelectrode	**Jsc(mAcm-2)**	**Voc(V)**	**FF**	**Eff(%)**	**Reference**
TiO_2 nanoparticle	18.1	0.91	0.78	13	16
TransparentTiO_2 nanotube	18.5	0.77	0.64	9.1	17
TiO_2 nanorod	16.52	0.772	0.746	9.5	18
TiO_2 nanotube on Ti coated TCO	15.8	0.73	0.59	6.89	19
TiO_2 microflowers	1.255	0.573	0.26	3.72	20
TiO_2 nanowires	17.5	0.75	0.47	6.2	21
TiO2 fusiform	10.13	0.68	0.57	4.68	22
TiO_2 nanopetals	10.54	0.7	0.7	5.3	23
TiO_2 nanochains	15.95	0.75	0.61	7.46	24
TiO_2 3D dendrites	14.52	0.72	0.68	7.2	25
TiO_2 hollow urchin	17.17	0.612	0.647	7.16	26
TiO_2 inverse opal	6	0.75	0.62	2.8	27
TiO_2 doped with tungsten	15.1	0.73	0.67	7.42	28
TiO_2 doped with scandium	19.1	0.752	0.68	9.6	29
TiO_2 doped with indium	16.97	0.716	0.61	7.48	30
TiO_2 doped with boron	7.85	0.66	0.66	3.4	31
TiO_2 doped with flourine	11	0.754	0.76	6.31	32
TiO_2 doped with carbon	20.38	0.73	0.57	8.55	33
ONT/FTO	10.65	0.7	0.7	5.32	34
TiO_2 NPs/TiO2 NTs	16.59	0.69	0.56	6.29	35
TiO_2 doped with copper	6.84	0.591	0.56	2.28	36
7.5%SnO_2 doped TiO_2	14.53	0.79	0.58	6.7	37
TiO_2, $Y_{1.86}Eu_{0.14}WO_6$	12.3	0.757	0.43	3.9	38

IV. APPLICATION OF DSSC

The dye-sensitized solar cells market is bifurcated on basis of application into portable charging, BIPVs, BAPVs, embedded electronics, outdoor advertising, solar chargers, wireless keyboards, emergency power in military, AIPVS, and others (light intensity meters and consumer appliances).

BIPVs category dominated the dye-sensitized solar cells market, contributing a share of more than 20.0%, in terms of value, in 2017. This can be attributed to the properties of dye-sensitized solar cells such as low-weight, easy installation, and a high performance-to-weight ratio. These enable easy installation and retrofitting of these cells in building envelopes like rooftops, louvres, glazed facades, and ceilings.

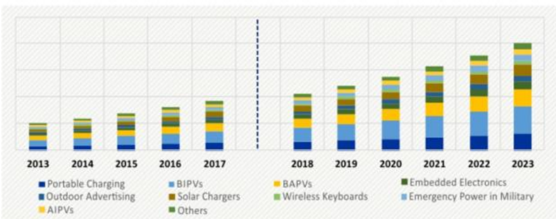

Fig3:DSSC Market by application, square meter(2013-2023)

The low-cost fabrication of dye-sensitized solar cells and no requirement of structural support material for modules such as beams envisages economic advantage in the building construction, due to possibility of price substitution of a building element from the price of panels. These factors are likely to drive the market in future.

Low power production efficiency of dye-sensitized solar cells can be viewed as the key factor restraining the dye-sensitized solar cells market growth. Silicon-based cells have a higher cost, but they are more efficient and have a power production efficiency of 12–15%, which is a slightly higher than the efficiency of these cells (which is around 11%). The global annual growth rate in DSSC market by application in a 10-year period is shown in Figure 3.

V. CONCLUSION

Dye-sensitized solar cells (DSSCs) have been widely studied due to several advantages, such as low cost-to-performance ratio, low cost of fabrication, functionality at wide angles and low intensities of incident light, mechanical robustness, and low weight. This article provides a comprehensive summary of the techniques and modifications done in the TiO_2 photoanodelayer to improve the performance of DSSCs. In particular, this review highlights a huge pool of studies that report improvements in the efficiency of DSSCs using TiO_2, which exhibit better electron transport. However, a brief explanation has been given to greater understand the working and components. The application of these nanostructured photoanodematerials and their impact on the device efficiency has been described in detail. Research and innovation in the dye-sensitized solar cells market help in mass commercialization of these cells.

REFERENCES

[1]. Yunfei Shang, Shuwai Hao,Chunhui Yang, Guanying Chen, Enhancing solar cell efficiency using photon upconversion materials, *Nanomaterials 5(4)*,2015,1782-1809.
[2]. Grätzel, M. Recent Advances in Sensitized Mesoscopic Solar Cells. *Acc. Chem. Res. 42*,2009, 1788–1798.
[3]. Shahan Shah, N.N.S. Baharun, S.N.F. Yusuf, A.K. Aro, Efficiency Enhancement of Dye-Sensitized Solar Cells (DSSCs) using Copper Nanopowder (CuNW) in TiO_2 as Photoanode *IOP Conf. Series: Materials Science and Engineering 515 012002*, 2019,1-10.
[4]. Kakiage, K.; Aoyama, Y.; Yano, T.; Oya, K.; Fujisawa, J.-i.; Hanaya, M, Highly-efficient dye-sensitized solar cells with collaborative sensitization by silyl-anchor and carboxy-anchor dyes. *Chem. Commun. 51*, 2015,15894–15897.
[5]. B. O'Regan and M. Gratzel, A low-cost, high-efficiency solar cell based on dye-sensitized colloidal TiO_2 films, *Nature, vol. 353, no. 6346*,1991, 737–740.
[6]. M. Nisha, S. Anusha, A. Antony, R. Manoj, and M. K. Jayaraj,Effect of substrate temperature on the growth of ITO thin films, *Applied Surface Science, vol. 252, no. 5*, 2005, 1430–1435.
[7]. B.-X. Lei, J.-Y. Liao, R. Zhang, J. Wang, C.-Y. Su, and D.-B. Kuang, Ordered crystalline TiO_2 nanotube arrays on transparent FTO glass for efficient dye-sensitized solar cells,*The Journal of Physical Chemistry C, vol. 114, no. 35*, 2010, 15228–15233.
[8]. M. K. Nazeeruddin, A. Kay, I. Rodicio et al., Conversion of light to electricity by cis-X2bis(2,2'-bipyridyl-4,4'-dicarboxylate)ruthenium(II) charge-transfer sensitizers (X = Cl-, Br-, I-, CN-, and SCN-) on nanocrystalline TiO2 electrodes, *Journal of the American Chemical Society, vol. 115, no. 14*, 1993,6382–6390.
[9]. M. K. Nazeeruddin, S. M. Zakeeruddin, R. Humphry-Baker et al., Acid-base equilibria of (2,2'-bipyridyl-4,4'-dicarboxylic acid)ruthenium(II) complexes and the effect of protonation on charge-transfer sensitization of nanocrystalline titania, *Inorganic Chemistry, vol. 38, no. 26*,1999, 6298–6305.
[10]. M. K. Nazeeruddin, P. Pechy, and M. Gratzel, Efficient panchromatic sensitization of nanocrystalline TiO_2 films by a black dye based on a trithiocyanato-ruthenium complex, *Chemical Communication, no. 18*,1997, 1705–1706.
[11]. P. Wang, C. Klein, R. Humphry-Baker, S. M. Zakeeruddin, and M. Gratzel, A high molar extinction coefficient sensitizer for stable dye-sensitized solar cells, *Journal of the American Chemical Society, vol. 127, no. 3*,2005, 808–809.
[12]. C.-Y. Chen, M. Wang, J.-Y. Li et al., Highly efficient light harvesting ruthenium sensitizer for thin-film dye-sensitized solar cells, *ACS Nano, vol. 3, no. 10*,2009, 3103–3109.
[13]. F. Gao, Y. Wang, D. Shi et al., Enhance the optical absorptivity of nanocrystalline TiO_2 film with high molar extinction coefficient ruthenium sensitizers for high

performance dyesensitized solar cells, *Journal of the American Chemical Society, vol. 130, no. 32*,2008, 10720–10728,

[14]. J. Wu, Z. Lan, S. Hao et al., Progress on the electrolytes for dyesensitized solar cells, *Pure and Applied Chemistry, vol. 80, no. 11*,2008,2241–2258.

[15]. A. Latini, F. K. Aldibaja, C. Cavallo, and D. Gozzi, Benzonitrile based electrolytes for best operation of dye sensitized solar cells, *Journal of Power Sources, vol. 269*,2014, 308–316,

[16]. S. Mathew, A. Yella, P. Gao, R.H. Baker, B.F.E. Curchod, N.A. Astani, Tavernelli, U. Rothlisberger, M.K. Nazeeruddin, M. Gr€atzel, Dye-sensitized solar cells with 13% efficiency achieved through the molecular engineering of porphyrin sensitizers, Nature *Chemistry, 6*,2014, 242-247.

[17]. C.J. Lin, W.Y. Yu, S.H. Chien, Transparent electrodes of ordered opened-end TiO_2-nanotube arrays for highly efficient dye-sensitized solar cells,*J. Material Chemistry 20*,2010, 1073-1077.

[18]. B.H. Lee, M.Y. Song, S.Y. Jang, S.M. Jo, S.Y. Kwak, D.Y. Kim,Charge Transport Characteristics of High Efficiency Dye-Sensitized Solar Cells Based on Electrospun TiO_2 Nanorod Photoelectrodes,*Journal of Physics Chemistry C 113*,2009, 21453-21457.

[19]. O.K. Varghese, M. Paulose, C.A. Grimes, Long vertically aligned titania nanotubes on transparent conducting oxide for highly efficient solar cells ,*Nat. Nano 4*,2009, 592-597

[20]. P.B. Patil, S.S. Mali, V.V. Kondalkar, N.B. Pawar, K.V. Khot, C.K. Hong, P.S. Patil,P.N. Bhosale, A facile and low cost strategy to synthesize Cd1-xZnxSe thin films for photoelectrochemical performance: Effect of zinc content ,*RSC Adv. 4*,2014, 47278-47286.

[21]. D. Lee, Y. Rho, F.I. Allen, A.M. Minor, S.H. Ko, C.P. Grigoropoulos, Synthesis of hierarchical TiO_2 nanowires with densely-packed and omnidirectional branches,*Nanoscale 5*,2013, 1147-11152.

[22]. K. Fan, W. Zhang, T. Peng, J. Chen, F. Yang, Application of TiO_2 Fusiform Nanorods for Dye-Sensitized Solar Cells with Significantly Improved Efficiency,*J. Phys. Chem. C115* 2011, 17213- 17219.

[23]. P.C. Shih, J.D. Peng, C.P. Lee, R.Y.Y. Lin, T.C. Chu, R. Vittal, K.C. Ho, Multi-functional TiO_2 Microflowers with Nanopetals as Scattering Layer for Enhanced Quasi-Solid-State Dye Sensitized Solar Cell Performance,*Chem Eletro Chem vol 1 (3)*,2014, 532-535.

[24]. C. Chen, J. Wang, Z. Ren, G. Qian, Z. Wang, One-dimension TiO_2 nanostructures: oriented attachment and application in dye- sensitized solar cell,*CrystEngComm 16*,2014, 1681-1686.

[25]. Z. Sun, J.H. Kim, Y. Zhao, D. Attard, S.X. Dou, Morphology-controllable1D–3D nanostructured TiO_2 bilayer photoanodes for dye-sensitized solar cells, *Chem. Commun. 49(10)*,2013, 966-968.

[26]. S.S. Mali, H. Kim, C.S. Shim, P.S. Patil, J.H. Kim, C.K. Hong, Surfactant free most probable TiO_2 nanostructures via hydrothermaland its dye sensitized solar cell properties,*Sci. Rep.*,2013, 3004.

[27]. J.H. Shin, J.H. Kang, W.M. Jin, J.H. Park, Y.S. Cho, J.H. Moon, Langmuir ,Facile Synthesis of TiO_2 Inverse Opal Electrodes for Dye-Sensitized Solar Cells,*ACS Publications,27, 2,* 2011, 856–860

[28]. Tong Z, Peng T, Sun W, Liu W, Guo S, Zhao XZ Introducing an Intermediate Band into Dye-Sensitized Solar Cells by W6+ Doping into TiO_2 Nanocrystalline Photoanodes. *J Phys Chem C 118(30):*,2014,16892–16895.

[29]. Latini A, Cavallo C, Aldibaja FK, Gozzi D, Efficiency Improvement of DSSC Photoanode by Scandium Doping of Mesoporous Titania Beads,*J Phys Chem C 117(48)*,2014,25276–25289.

[30]. Bakhshayesh AM, Farajisafiloo N ,Efficient dye-sensitised solar cell based on uniform In-doped TiO_2 spherical particles,*Applied Physics A 120(1)*,2015, 199–206.

[31]. Subramanian A, Wang HW , Effects of boron doping in TiO_2 nanotubes and the performance of dye-sensitized solar cells,*Appl Surf Sci 258(17)*,2012, 6479–6484.

[32]. Song J, Yang HB, Wang X, Khoo SY, Wong CC, Liu XW, Li CM, Improved utilization of photogenerated charge using fluorine-doped TiO_2 hollow spheres scattering layer in dye-sensitized solar cells. *ACS Appl Mater Interfaces 4(7)*,2012,3712–3717.

[33]. Tabari-Saadi Y, Mohammadi MR ,Efficient dye-sensitized solar cells based on carbon-doped TiO_2 hollow spheres and

nanoparticles. *J Mater Sci Mater Electron 26(11)*,2015, 8863–8876.

[34]. Lin J, Chen J, Chen X ,High-efficiency dye-sensitized solar cells based on robust and both-end-open TiO_2 nanotube membranes,*Nanoscale Res Lett 6:475*,2011,1-5.

[35]. Song CB, Qiang YH, Zhao YL, Gu XQ, Zhu L, Song CJ, Liu X ,DyesensitizedSolar Cells Based on Graphene-TiO_2 Nanoparticles/TiO_2 Nanotubes Composite Films. *Int J Electrochem Sci 9*,2014,8090–8096.

[36]. Patle LB, Chaudhari AL ,Performance of DSSC with Cu Doped TiO_2 Electrode Prepared by Dip Coating Technique. *Int J Sci Eng Res 7(8)*,2016,1004–1009.

[37]. Mao X, Zhou R, Zhang S, Ding L, Wan L, Qin S, Chen Z, Xu J, Miao S, High Efficiency Dye-sensitized Solar Cells Constructed with Composites of TiO_2 and the Hot-bubbling Synthesized Ultra-Small SnO_2,*Nanocrystals. Sci Rep 6:19390*,2016

[38]. Llanos J, Brito I, Espinoza D, Sekar R, Manidurai P A down-shifting Eu3 +−doped Y2WO6/TiO_2 photoelectrode for improved light harvesting in dye-sensitized solar cells,*R Soc open sci 5:171054*,2018,1-10.

Reshmi Krishnan S. "Nanomaterials for photoelectrodes in dye sensitized solar cells-a Review."*International Journal of Engineering Research and Applications (IJERA)*, vol.11 (2), 2021, pp 10-17.