

Dye-sensitized solar cells using some organic dyes as photosensitizers

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Eight organic dyes are used as sensitizers for dye-sensitized solar cells. These dyes are eosin Y, aniline blue, bromophenol blue, alcian blue, methyl orange, crystal violet, fast green, and carbol fuchsin. The absorption spectra of these dyes are carried out by UV–VIS spectrophotometry. Dye-sensitized solar cells are assembled using nanostructured, mesoporous TiO₂ films. Photovoltaic parameters of the fabricated cells are investigated and the highest overall conversion efficiency of 0.399% is obtained for the dye-sensitized solar cell sensitized with eosin Y.

Keywords: dye-sensitized solar cells, synthetic dyes.

1. Introduction

Dye-sensitized solar cells (DSSCs) were developed in 1991 by O'REGAN and GRÄTZEL [1]. DSSCs are considered the third generation of photovoltaic devices for the conversion of visible light into electrical energy [2]. This new type of solar cells is based on the photosensitization produced by the dyes on wide bandgap semiconductors such as TiO₂. This sensitization is produced by the dye absorption of part of the visible light spectrum. DSSCs are low cost solar cells because of inexpensive materials and the relative ease of the fabrication process. Recent studies have shown that semiconducting materials such as TiO₂ and ZnO have been successfully used as photoanodes when a dye is adsorbed at the surface of the porous layer of the semiconductor [3–11]. Both synthetic [3–6] and natural [7–11] dyes have been widely investigated as photosensitizers for DSSCs. In the following, some significant works employing synthetic dyes are presented.

New alkyl-functionalized organic dyes, MK-1 and MK-2, were designed and synthesized for DSSCs in 2006 [3]. Based on the MK-2 dye, a high performance (efficiency $\eta = 7.7\%$, short-circuit current density $J_{sc} = 14.0 \text{ mA/cm}^2$, open-circuit voltage $V_{oc} = 0.74 \text{ V}$, and fill factor $FF = 0.74$) was achieved under AM 1.5 irradiation

(100 mW/cm²). In 2009, the use of a diazapentadiene derivative and two compounds of triazole derivatives as photosensitizers for DSSCs was demonstrated [4]. In 2013, seven flavylum salt dyes were employed for the first time as sensitizers for DSSCs. The best performance was obtained for the DSSC based on the novel compound 7-(*N,N*-diethylamino)-3',4'-dihydroxyflavylium which produced a 2.15% solar energy-to-electricity conversion efficiency, under AM 1.5 irradiation with a short-circuit current density of 12.0 mA/cm², a fill factor of 0.5, and an open-circuit voltage of 0.355 V [5]. In 2013, a set of efficient sensitizers based on the zinc-porphyrin structure was designed for DSSCs [6]. The geometries, electronic properties, light harvesting efficiency, and electronic absorption spectra of these sensitizers were studied using the density functional theory and time-dependent density functional theory calculations. Fast production of ZnO nanorods by the bottom up approach using the arc discharge method in deionized water was carried out [12]. DSSCs were successfully produced via different ruthenium based dyes and ferrocene liquid electrolyte using synthesized ZnO nanorods modified photoanodes [12]. It has been found that DSSCs made with N719 dye is the most efficient with photoconversion of approximately 7% compared to the other dyes. The fabrication and photovoltaic characterization of pure and dodecyl benzene sulfonic acid-doped polyaniline microrods polymer/*n*-Si heterojunction solar cells were reported [13]. A new and promising DSSC bilayer design was developed using an Fe²⁺/Fe³⁺ (ferrocene) liquid electrolyte and natural dyes extracted from *Hypericum perforatum L.*, *Rubia tinctorum L.* and *Reseda luteola L.* [14]. Five aldimine derivatives were prepared by condensation of the appropriate amine with salicylaldehyde and 4-aminobenzoic acid with 2-thiophene carboxaldehyde and used as photosensitizers for DSSCs [15].

In this work, DSSCs were fabricated using TiO₂ nanoparticles as a semiconducting layer. The synthetic photosensitizers used were eosin Y, aniline blue, bromophenol blue, alcian blue, methyl orange, crystal violet, fast green, and carbol fuchsin. These dyes were characterized by UV–VIS spectrophotometry. The photovoltaic properties of the fabricated DSSCs were investigated.

2. Experimental work

The dyeing solution was prepared by adding 4 mg of the dye powder to 20 ml of ethyl alcohol. The solutions were left at room temperature for one day.

Fluorine-doped SnO₂ (FTO) conductive plates with sheet resistance of 15 Ω/cm² and transmission >80% (Xinyan Technology Ltd., Hong Kong) were cut into pieces of dimensions 1.6 cm×1.6 cm. The sheets were cleaned in a detergent solution using an ultrasonic bath for 9 min, rinsed with water and ethanol, and then dried in an oven at 60 °C for 30 min. The TiO₂ paste was prepared by mixing 50 mg of TiO₂ nanoparticles with the size of 10–25 nm (US Research Nanomaterial, Inc., USA) and 50 mg of polyethyleneglycol, then grinding the mixture for half an hour until a homogeneous paste was obtained. Thin films of TiO₂ paste were deposited on the transparent conducting FTO coated glass using the doctor blade technique. After

spreading the paste, the films were left to dry for 5 min before removing the tape and placing the film in an oven at 70 °C for 30 min. The films were then sintered at 450 °C for 40 min and cooled down to 70 °C. The thickness of the sintered films was measured using an Olympus polarizing microscope (BX53-P) equipped with a DP73 camera and was found to be about 22 μm. The films were then dyed for 16 hours under dark. The dyed TiO₂ electrode and a counter electrode fabricated from FTO-coated glass, on which a platinum catalyst layer was sputtered, were assembled to form a solar cell by sandwiching a redox (I⁻/I₃⁻) electrolyte solution. The electrolyte solution is composed of 2 ml acetonitrile (ACN), 8 ml propylene carbonate (p-carbonate), 0.668 g (KI), and 0.0634 g iodine (I₂).

The absorption spectra measurements of the dyes in ethyl alcohol solution were performed using a UV–VIS spectrophotometer (Thermoline Genesys 6) in the spectral range from 300 to 800 nm. The *J–V* characteristic curves of all fabricated cells were conducted under illumination using a National Instruments data acquisition card (USB NI 6251) in combination with a Labview program. The *J–V* curves were measured at 100 mW/cm² irradiations using a high pressure mercury arc lamp with an IR filter.

3. Results

The UV–VIS absorption spectra of all dyes were investigated. It was found that the solutions of eosin Y, aniline blue, bromophenol blue, alcian blue, methyl orange, crystal violet, fast green, and carbol fuchsin have absorption peaks in the visible region at 520 nm, 625 nm, 426 nm, (624 nm and 672 nm), 654 nm, 588 nm, 620 nm, and 550 nm, respectively. Figure 1 shows the UV–VIS absorption spectra of eosin Y, bromophenol blue, aniline blue, carbol fuchsin, alcian blue, methyl orange, crystal violet, and fast green dissolved in ethyl alcohol.

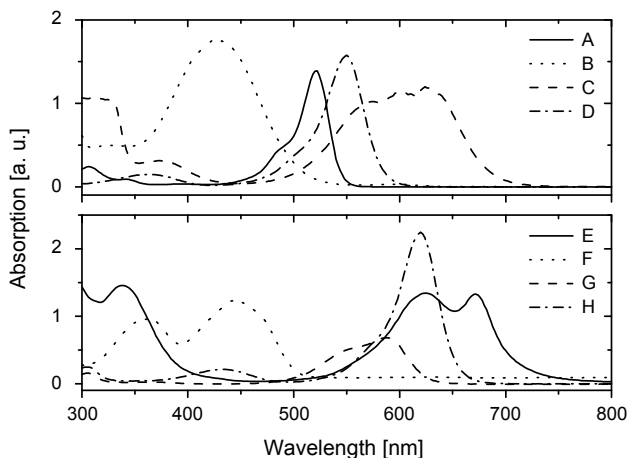


Fig. 1. The absorption spectra of eosin Y (A), bromophenol blue (B), aniline blue (C), carbol fuchsin (D), alcian blue (E), methyl orange (F), crystal violet (G), and fast green (H) dissolved in ethyl alcohol.

Photovoltaic tests of the fabricated DSSCs using these dyes as sensitizers were performed by measuring the J - V curve of each cell under irradiation with white light (100 mW/cm^2) from a high pressure mercury arc lamp. Figure 2 shows the typical J - V curves of the DSSCs sensitized with eosin Y, bromophenol blue, aniline blue, alcian blue, methyl orange, crystal violet, fast green, and carbol fuchsin.

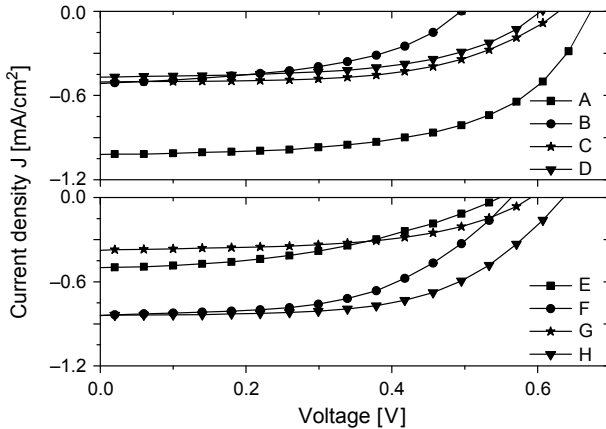


Fig. 2. Current density–voltage curves for the DSSCs sensitized by eosin Y (A), bromophenol blue (B), aniline blue (C), alcian blue (D), methyl orange (E), crystal violet (F), fast green (G), and carbol fuchsin (H).

The performance of the synthetic dyes as sensitizers for DSSCs was evaluated by short circuit current J_{sc} , open circuit voltage V_{oc} , fill factor FF, and energy conversion efficiency η . The parameters J_{sc} and V_{oc} of each cell were evaluated from its J - V curve. The DSSC output power was calculated as $P = JV$ using the J - V data. The maximum power point P_{max} of each cell was then obtained. The current density J_m and voltage V_m corresponding to the maximum power point were then obtained. The corresponding parameters FF and η of each cell were calculated [9]. The photovoltaic parameters of the fabricated cells are presented in Table 1. As can be seen from the table, the short circuit current density has a maximum value of 1.020 mA/cm^2 for the DSSC sensitized with the eosin Y, and a minimum value of 0.374 mA/cm^2 for the DSSC sensitized with the fast green. The DSSCs sensitized eosin Y, crystal violet, and carbol fuchsin exhibited high short circuit current densities whereas the DSSCs sensitized with fast green, alcian blue, and methyl orange showed relatively low short circuit current densities. The open circuit voltage ranged between 0.549 V for the DSSCs sensitized with bromophenol blue and methyl orange extracts and 0.671 V for the cell dyed with eosin Y. The fill factor of the fabricated cells changed from 42.4% to 59.6%. The lowest fill factor was observed for the cell dyed with methyl orange whereas the highest fill factor was obtained for that sensitized with carbol fuchsin. The highest output power and efficiency were obtained for the DSSC sensitized with eosin Y where the efficiency of the cell reached 0.399%. The DSSCs sensitized with eosin Y, carbol fuchsin, and crystal violet showed relatively high values of the output power and efficiency

Table 1. Photovoltaic parameters of the fabricated DSSCs.

Dye	λ_{\max} [nm]	J_{sc} [mA/cm ²]	V_{oc} [V]	J_m [mA/cm ²]	V_m [V]	FF	η [%]
Eosin Y	520	1.020	0.671	0.787	0.509	0.581	0.399
Aniline blue	625	0.505	0.630	0.410	0.438	0.564	0.117
Bromophenol blue	426	0.513	0.549	0.350	0.337	0.479	0.120
Alcian blue	624, 672	0.470	0.600	0.358	0.483	0.556	0.156
Methyl orange	651	0.500	0.549	0.341	0.341	0.424	0.115
Crystal violet	588	0.839	0.566	0.665	0.377	0.526	0.249
Fast green	620	0.374	0.600	0.288	0.416	0.533	0.117
Carbol fuchsin	550	0.841	0.608	0.700	0.436	0.596	0.303
Ru complex		12.500	0.600	10.220	0.381	0.460	2.58

whereas those sensitized with methyl orange, fast green, and aniline blue exhibited relatively low values of the output power and efficiency. These results are comparable to those obtained for the DSSCs sensitized by other chemical dyes in previous work [4]. Moreover, Table 1 shows the photoelectrochemical parameters of the DSSCs sensitized with Ru complex cis-dicyano-bis(2,2'-bipyridyl-4,4'-dicarboxylic acid) ruthenium(II), Ruthenizer 505, (Solaronix, Switzerland), which is widely used in DSSCs. As can be seen, most of the fabricated DSSCs in this work exhibited V_{oc} higher than that of the DSSC sensitized by Ru complex. The J_{sc} of all fabricated cells were very low compared to that of the DSSC sensitized by the Ru complex. The low short circuit current may be attributed to the incompatibility between the energy of the excited state of the adsorbed dye and the conduction band edge of TiO₂. Moreover, the ground state of dye molecules may be considerably shifted with respect to the redox potential of I⁻/I₃⁻. Fast charge recombination rate and loss resulting from various competitive processes can also be responsible for the low short circuit current density. As mentioned in Section 2, the thickness of the TiO₂ film was measured to be 22 μ m which is a relatively large compared to the optimum value (~15 μ m). Thick films increase the series resistance of the cell which in turn reduces the current density.

The best performance was obtained from the DSSC sensitized by eosin Y where the efficiency of the cell reached 0.399%. There are several dyes named eosin, and specifically the one most commonly used to counterstain hemalum is eosin Y. It has a molecular formula C₂₀H₈Br₄O₅ and molecular weight of 647.89. Eosin Y is a pink water soluble acid dye which also displays yellow-green fluorescence. It is used in

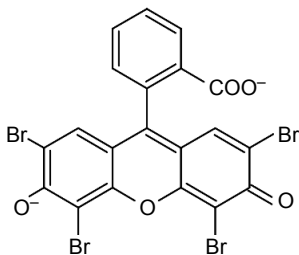


Fig. 3. Chemical structure of eosin Y.

the fields of dyeing, printing, and as a fluorescent pigment. Moreover, it is used in paint and dye industries because of its vivid color. The toxic nature of the dye is still not quantified much but its high content in living systems is proved to be harmful. The chemical structure of eosin Y is shown in Fig. 3.

4. Conclusion

In this paper, dye-sensitized solar cells (DSSCs) were assembled using eight synthetic dyes as sensitizers for nanocrystalline TiO_2 photoelectrodes. Photovoltaic parameters of the fabricated DSSCs were determined under 100 mW/cm^2 illumination. It is found that the best performance among the tested dyes was obtained from the DSSC sensitized by eosin Y where the efficiency of the cell reached 0.399%.

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