Fabrication and properties of high efficiency dye-sensitized solar cells (DSSCs) with photon absorption optimization

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Abstract. Dye-sensitized solar cells (DSSCs) have attracted much attention because these unconventional solar cells exhibit high performance and have the potential for low-cost production. To achieve higher performances for solar cells based on organic dyes, comparable to those for solar cells based on the color spectrum, the light absorption of organic dyes is required. In a DSSC, the electrodes are surrounded by a thin shell and a dye monolayer for 3 colors of dyes. Based on the optical properties, the large absorption of light can be given in a colorless dye with a wavelength of the most extensive. Combination colors from three-band basic colors, such as red (R), green (G) and blue (B) can create the optimum light absorption. The Incident Photon-to-charge Carrier Efficiency (IPCE) will be high if the absorption spectrum graph of dye color is large too, therefore the Dye-Sensitized Solar Cell (DSSC) will produce photon current (I) or high short-circuit current (Isc). To ensure solid surface coverage, the dye must have a high absorption coefficient on TiO2. The electrodes can be maximized with reduced layer thickness so the possibility of recombination decreases with decreasing electrode thickness and thicker electrolytes with low vapor pressure can be applied. The longer the wavelength, the less absorption will cause a small portion of the sun's spectrum to disappear. The experiment showed that a combination of three band colors of dye is obtained the largest light absorption. This black color proved to have the greatest light absorption. The experiment can result for the exhibit a high open-circuit voltage VOC of 320 mV, open-circuit current IOC of 0.045 mA, maximum voltage Vmax of 134 mV, maximum current Imax of 0.044 mA, maximum power Pmax of 5.89 µW, Fill Factor (FF) of 42 and a power conversion efficiency of 9.1%.

1. Introduction

Dye-sensitized solar cells (DSSCs) have been extensively evolved for the past two decades to improve their cell performance. From the commercialization point of view, the overall solar to electrical energy conversion efficiency should compete with other solar cells. But, due to structural restrictions of DSSC using the liquid electrolyte and a space requirement between two electrodes, the direct tandem construction of DSSCs by stacking of repeating units is highly limited. In this feature article, important research trials to overcome these barriers and a recent research trend to improve the light-harvesting strategies mainly panchromatic engineering, various tandem approaches such as parallel tandem, series tandem, p–n tandem, etc., have been briefly reviewed [1].

Solar cells or photovoltaic cells are devices that can convert sunlight energy into electrical energy. The photovoltaic effect is the basis of the process of converting sunlight (photons) into electricity. An interesting development of the current solar cell technology is the solar cell developed by Grätzel in 1991. This cell consists of a nanolayer (usually TiO2) that is immersed in photosensitizer (light-
Sensitized dye solar cells can convert sunlight which is photon energy into an electric current. The working principle of a sensitized dye solar cell begins when sunlight falling to the cell surface is absorbed by a dye solution that is sensitive to sunlight (also called a photosensitizer). As a result of this absorption of sunlight energy, electrons from the dye can be excited and go to the TiO2 layer which then continues to flow into the cable through a thin layer of conductor glass (electrodes). Meanwhile, the loss of electrons in the dye solution is replaced by the presence of electron donors from the iodine electrolyte solution through an oxidation-reduction reaction with a thin layer of carbon as a cathode.

The attachment group of the dye ensures spontaneously assembles as a molecular layer upon exposing the oxide film to a dye solution. This molecular dispersion ensures a high probability that, once a photon is absorbed, the excited state of the dye molecule will relax by electron injection to the semiconductor conduction band [2]. However, DSSC based on organic dyes has not yet achieved higher performance for solar cells based on organic dyes, comparable to solar cells based on the color spectrum, the absorption of light from organic dyes is required. The result is not optimal enough, because the use of 1 (one) color of the dye sent, photons from solar energy will only absorb 1 (one) wavelength that is following the energy [3].

The objective of this paper is to develop a new structure of DSSC with three-band colors of dyes derivatives from some simple well-known organic dyes and experimentally determine the efficiency of DSSC based on titanium dioxide. Therefore, it is necessary to obtain DSSC equivalent circuits to accelerate the development of practical DSSC based photovoltaic modules.

2. Theory
Dye-Sensitized Solar Cell (DSSC) are often also called Grätzel cells. The high efficiency of converting solar energy into DSSC is one of the attractions of developing research on DSSC in various countries lately, aside from the simple production process and low production costs [2]. As mentioned in the last section, a light sensitized organic dye functions as the photon absorber, leaving the charge carrier function to the semiconductor.

The mechanism of DSSC is similar to that of a solar cell. Photoexcitation at a monolayer of organic dye results in the injection of an electron into the conduction band of oxide. Then, organic dye restores its original electron configuration by electron donation from the electrolyte, usually an organic system containing redox couples [4]. The heart of this solar cell is composed of nano-particles of mesoporous (with the pore width of 2-50 nm) oxide layer, which allows electronic conduction taking place. Since inorganic nano-particles have several advantages such as size tenability and high absorption coefficients, it is always the first choice when considering the cost and performance, etc.

The material choice is mainly TiO2(Anatase), but alternatives such as ZnO and Nb2O5 have been investigated as well [5]. Besides, experimental results showed mesoporous TiO2 layer has a highly efficient charge transport [6]. One drawback of solar cells this photoelectrochemical is of low stability, mainly due to degradation and leakage of electrolytes liquid used. Therefore, lately the development of photoelectrochemical solar cell research directed at the use of solid electrolytes for reduce electrolyte degradation and leakage can increase cell stability, for example, electrolytes polymer-based containing redox or coupling based on organic or inorganic materials as hole conductor.

3. Methods
The prototype of Dyes of Dye-Sensitized Solar Cells (DSSCs) with three-band colors of dyes was constructed. Based on the scientific references found in the earlier literature chapter, details of procedures to conduct the experiments will be presented. The preparation of dyes will also be provided in this section. The different techniques will be demonstrated and discussed in this section as well. The steps of the experiment for DSSC optimization are shown on the flow chart following figure 1.
4. Result and discussion
The results from each experiment mentioned in the methodology chapter are presented and analyzed. Explanations are proposed for each result. If not mentioned specifically, all of the results were measured under 298K, 1 atm pressure with the illumination of fluorescent light. Unless specified, all of the measurements in tables have units of Volts.

4.1. Colors spectrums irradiances
This step is producing natural dyes from food color dyes, which consisted of 3 (three) basic colors, such as colors of red, green and blue. Performed using a UV-Vis spectrophotometer measured at wavelength 400-700 nm. The color spectrum of dyes are:

![Color simulated incident photon flux density for basic colors spectrums](image)

The absorption spectrum showed the absorption of dye at a certain wavelength. The absorption of red solution at a wavelength of around 507 nm, the absorption of green solution at a wavelength of around 600 nm dan the absorption of blue solution at a wavelength of around 629 nm.
4.2. Optimization properties of DSSC device

4.2.1. Variation of TiO2 layer thickness and prolonged heating. Thickness variation of the TiO2 layer will affect the resistance of the layer because TiO2 material is a semiconductor device which effected by the resistance value. The relation of thickness and resistance value of the TiO2 layer can be shown in table 1.

| No  | Thickness (mm) | Resistance (Ohm/cm²) |
|-----|----------------|----------------------|
| 1   | 0.6            | 9                    |
| 2   | 1.0            | 12                   |
| 3   | 1.4            | 13                   |

From Table 1, The thickness of the Titania layer affected the absorption of the dye. Increasing Titania film thickness can increase of absorption of the dye. But the optimum thickness is required because if the high thickness of the layer will be high resistance and easy to crack.

Heating is done to accelerate the evaporation of water content contained in the TiO2 layer and to strengthen the adhesion of the TiO2 layer on the glass. However, prolonged heating TiO2 coating will crack as shown in the table below the heating test (with a layer thickness of 0.6 mm).

| No  | Prolonged heating (minute) | Resistance (Ohm) | Condition          |
|-----|-----------------------------|------------------|--------------------|
| 1   | 10                          | 5                | TiO2 layer no crack|
| 2   | 30                          | 9                | TiO2 layer no crack|
| 3   | 60                          | 9                | TiO2 layer crack   |

4.2.2. Dye concentration and soaking time of dye

Immersion dye is done to provide a dye into the TiO2 layer using absorption. Soaking is done by placing a layer of the liquid dye so that the dye can be absorbed by a layer of TiO2. However, the time of immersion is also taken into account, if it is too short then the dye absorption is not optimal whereas if too long it will flake off, as shown in table 3.

| No  | Time of Soaking (minute) | Condition                  |
|-----|--------------------------|----------------------------|
| 1   | 5                        | TiO2 layer no flake off    |
| 2   | 10                       | TiO2 layer no crack        |
| 3   | 30                       | TiO2 layer flake off       |

Optimization is done by dissolving the dye concentration of the dye with the electrolyte solvent effect on the resistance value. The test results are shown in Table 4.

| No  | Concentration (Mol) | Resistance (Ohm) |
|-----|---------------------|------------------|
| 1   | 0.08                | 40               |
| 2   | 0.1                 | 15               |
| 3   | 0.12                | 10               |

Table 1. Variation of TiO2 layer thickness

Table 2. Variation of TiO2 layer thickness

Table 3. Variation of soaking TiO2 coating in the dye

Table 4. Concentration coloring dye
4.3. Iodine concentration

Variations in the concentration of iodine (I2) is required to obtain the optimal value by measuring the resistance value. Following the equivalent circuit device DSSC, the concentration of iodine affects the value of the series resistance in these devices, the higher the value, the series resistance of the resulting current will be smaller, and vice versa. Relations iodine concentrations can be indicated in table 5.

| No | Concentration (Mol) | Resistance (Ohm) |
|----|---------------------|------------------|
| 1  | 0.025               | 75               |
| 2  | 0.05                | 70               |
| 3  | 0.075               | 60               |

From the optimization experiments on the fabrication of DSSC solar cells, optimal parameters can be reported in table 6.

| No | Concentration (Mol) | Resistance (Ohm) |
|----|---------------------|------------------|
| 1  | The thickness of the TiO2 layer 0.6 mm |
| 2  | Prolonged heating TiO2 30 minutes |
| 3  | Dye concentration 60 (mmol/cm3) |
| 4  | Soaking time of dye 10 minutes |
| 5  | Iodine Concentration(I2) 0.075 (mmol/cm3) |

4.4. I-V characteristic

DSSC measurements were carried out using the curve method current and voltage. The purpose of this DSSC measurement to find out the effectiveness of solar cells that have been made in converting light energy into energy electricity. DSSC measurement using the I-V curve method use voltage variations to determine scale in determining DSSC efficiency. The magnitude in determining DSSC efficiency is voltage open circuit (Voc), open circuit current (Ioc), optimum voltage (Vmax), optimum current (Imax) and fill factor (FF)., we got graphics of I-V characterization of DSSC which is showed in Figure 3.

![Figure 3. I-V Curve of DSSC solar cell using black dye-sensitized](image)

According to the I-V curve in Figure 3, the performance of DSSC with the RGB color of dyes is better than a single dye in this research using red dye. Overall, the parameter performance of the solar
cell can be looked at from the values of the efficiency of the black dye of 9.1%. All parameter measurements can be shown in table 7.

| No. | Parameter       | Value |
|-----|-----------------|-------|
| 1.  | V_{oc}(mV)      | 320   |
| 2.  | I_{oc}(mA)      | 0.045 |
| 3.  | V_{max}(mV)     | 134   |
| 4.  | I_{max}(mA)     | 0.044 |
| 5.  | P_{max}(µW)     | 5.89  |
| 6.  | FF(%)           | 42    |
| 7.  | η(%)            | 0.091 |

5. Conclusion
The project overall was considered successful resulting from the data which agreed with the published results and the trends I have concluded from controlled experiments. In this research, the dyes are natural dyes with 3 (three) basic colors such as red, green and blue. At this moment, it hasn’t been compared to each color. The combination of three band colors of dye is obtained the largest light absorption. This black color proved to have the greatest light absorption. The experiment with colors variation of dye-sensitized resulted that in dye-sensitized solar cells that exhibit a high open-circuit voltage V_{oc} of 320 mV, open-circuit current I_{oc} of 0.045 mA, maximum voltage V_{max} of 134 mV, maximum current I_{max} of 0.044 mA, maximum power P_{max} of 5.89 µW, Fill Factor (FF) of 42 and a power conversion efficiency of 9.1%.

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