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Photodetector Characterization Based on DSSC (Dye-Sensitized Solar Cell)

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Abstract. A photodetector performance as a light sensor based on the design and material of DSSC (Dye-Sensitized Solar Cell) has been characterized. Oxide Semiconductor nanoparticle of TiO_2 and extracted natural dye are used to absorb and convert incident photon to electric energy using a sandwich structure of 1.5 x 1.5 cm^2 active area. The sensor materials were used include TCO (Transparent Conductive Oxide) glass as substrate, electrolyte solution and carbon. Method of TiO_2 deposition to the TCO glass substrate is spin coating and firing at 1,500 rpm and 450 °C, respectively. Natural dye was extracted from green algae by a different variation of solution concentration according to the ratio of mass and volume. The chlorophyll absorbance was investigated by spectrophotometer at a wavelength of 300-800 nm. SEM (Scanning Electron Microscope) is used to observe TiO_2-coated TCO glass morphology. Fabricated sensors are characterized according to the electrical parameters of voltage and current towards light illuminance from the light source. This natural dye-based optical photodetector performance has been analysed to obtain linearity, sensitivity, uncertainty error, and other electrical transient response characteristics. The result of extracted chlorophyte absorbance shows a wavelength peak at 580 to 680 nm with different intensity; it indicates the visible light absorbance spectra occurred. Sensor measurement using light illumination up to 30,000 lux produces the highest rated voltage of 626.4 mV and current 78,7 (µA) at the ratio of 6:5 (m:v) solution. This sensor has a voltage sensitivity of 1,0875 mV/10lux and the current sensitivity of 0.0024 µA/lux. The voltage and current uncertainty error are 0.36% and 0.481%, respectively.

1. Introduction

A photodetector sensor is a light sensor that are often implemented for energy savings, image processing and other applications [1]. However, the existence of the optical and light sensors in the market unsuitable for general purposes. It is characterized by the materials used in the making of a sensor in the form of a semiconductor material such as CdS. These materials are assessed can absorb light with efficient, but how to get the material is fraught full risk. Photodetector from organic dye sensitization of large band-gap oxide semiconductor has been investigated for many years [2], [3], [4] due to that can be produced at very low cost. A major photo-electrochemical photodetector development was obtained with the introduction of fractal thin film dye-sensitized solar cells previously [5]. Many studies are realized on the dye used for sensitizing DSSC since it is the principal source of the photo-generated current by the cell. However, the price of this dye stays even higher.

Nevertheless, the natural dye becomes more real concurrent to an artificial one [6], as the efficiency of cell sensitized with this dye remains low [7], [8].

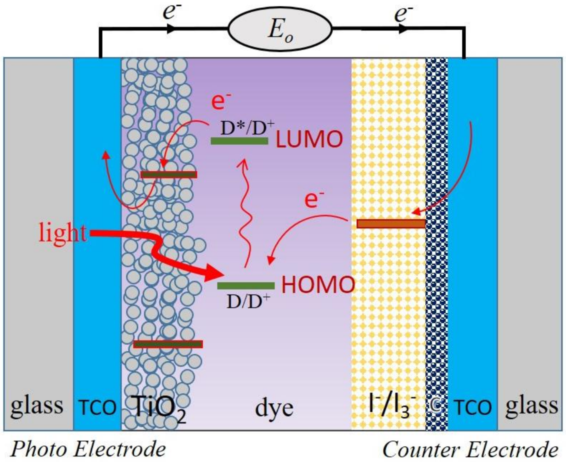

Figure 1. Basic Principle of Customized photodetector based on DSSC

The principle of photodetector based-dye and TiO_2 refers to DSSC [9] shown in Figure1. While the photons from the light source hit the DSSC, the energy of photons will be absorbed by the dye (*D*) that attaches to TiO_2 particles. Then the electron from the dye will receive energy, and the electrons will be exited condition while dyeing molecules electron in the excited condition (D^*) as shown in (1).

$$D + light \rightarrow D^* \quad (1)$$

The excited electrons from dye molecules will be injected to a conduction band of TiO_2 and the dye molecule in state oxidation (D^+) as shown in (2). Then the electron will be transferred to reference electrode.

$$D^* + TiO_2 \rightarrow e^-(TiO_2) + D^+ \quad (2)$$

Redox electron usually in the form of iodide and tri-iodide (I^-/I_3^-) that act as electron mediator then generate cycle in a cell. Tri-iodide from electrolyte will catch electrons that come from the outer circuit with the help of series carbon molecules as a catalyst. The excited electrons will return to the cell and react with electrolyte into the oxidized dye. An Equation (3) shows the electrolyte which provide replacement electrons for the oxidation dye.

$$D^+ + e^-(electrolyte) \rightarrow electrolyte + D \quad (3)$$

The standard structure of photodetector is using two TCO glass as the substrate the place of establishment of the photo electrode and counter electrode. The principle and the research photodetector from the development of DSSC using TiO_2 as the active layer with variation dye has been characterized in the previous research [10]. The TiO_2 not only has attractive oxide semiconductor for DSSC, but also suitable for sensor applications [11], [12]. For sensors performance, this research will be designed and analyzed the fabrication of photodetector with the dye chlorophyll green algae extraction with low temperature processing and competitive cost, considering Indonesia is rich in green algae.

2. Theoretical review

The Photodetector detects the photon or the electromagnetic wave. Modern physics study such as the mechanical quantum explains the photon dualism as a wave and a particle. Photon as a wave has wavelength λ, velocity, and also frequency. It is also explained how light produce the interference, diffraction, and also refraction phenomena. Photon as a particle has mass, momentum, and ability to fill the space. Energy of the photon depend on the light frequency or wavelength, the higher the frequency, the energy is bigger also. The conversion phenomena of this Grätzel cell-photodetector is one of photo electrochemical process using the light illuminance as the stimulus, and the voltage also the current as the output of the photodetector.

The static sensor parameters, such as transfer function, span or measured range, FSO (Full Scale Output), offset, linearity, sensitivity and repeatability are essential in sensor designing. FSO shows resulting output signal, displayed reading produced when the maximum measurement for a given device is applied. Span or measured range defines the maximum and minimum value of inputs and outputs of the sensor. Transfer function of the sensor characterizes an ideal output-input relationship. This function shows the output signal y generated by the sensor as an input (stimulus) x dependent shown in Equation (4).

$$y = f(x) \quad (4)$$

The unidimensional linear y_L and non-linear y_{NL} function are generally represented by Equation (5) and (6).

$$y_L = Sx + offset \quad (5)$$

$$y_{NL} = S(x) + offset \quad (6)$$

Linearity is defined as the maximum deviation from the linear characteristic as a percentage of the FSO. Sensitivity can be defined as the ratio of incremental output and incremental input as shown in Equation (7).

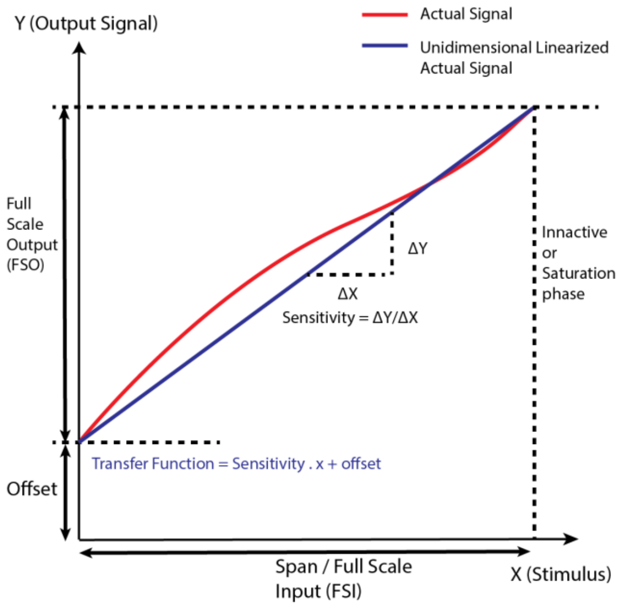

Figure 2. Sensor characteristic illustration

$$S = \frac{\Delta y}{\Delta x} \quad (7)$$

Offset shows a value of the output signal generated by the sensor when there is no stimulus. Assuming that *f(x)* is continuous □*x*, the offset can be determined by Equation (8).

$$offset = y(0) \quad (8)$$

Accuracy represents the closeness of the measured value with the actual value, and is expressed in the form of the maximum error (measured value – true value) as a percentage of full scale reading. Percentage of reading is defined by Equation (9).

$$\varepsilon_a\% = \frac{(y_m - y_t)}{y_t}100 \quad (9)$$

and percentage of full scale is defined by Equation (10).

$$\varepsilon_f\% = \frac{(y_m - y_t)}{y_{fso}}100 \quad (10)$$

Precision is indicated by the repeatability or reproducibility of an instrument. A precision instrument ϵ indicates that the successive reading would be very close, or in other words, the standard deviation σ_e of the set of measurements would be very small. Quantitatively, the precision can be expressed as (11).

$$\in = \frac{span}{\sigma_e} \quad (11)$$

Hence, repeatability ρ is represented by a value that is the same or similar to the previous value.

$$\rho\% = \frac{y_{\max} - y_{\min}}{FS} x100\% \quad \text{or} \quad \rho\% = \frac{\sigma_{\max} - \bar{y}}{FS} x100\% \quad (12)$$

The different between precision is the repeatability is the repeating value at the same value, and the precision is how exactly the repeating value to the previous value at the different unit.

3. Research method

3.1. Sensor Fabrication

In this research, the photodetector was fabricated using the natural dye extracted from green algae Chlorophyll. Three sample of fabricated sensors is performed with algae extraction and solvent concentration of 3:5 (sample 1), 4:5 (sample 2) and 6:5 (sample 3), respectively. Sample with ratio 3:5 were made from 30 grams of green alga leaf, 40 grams for ratio 4:5 and 60 grams for sample ratio 6:5. Green algae will be mashed until smooth and filter up to the extraction of green algae produced. Further extraction green algae produced, plugging extraction into 50 mL 100% ethanol and stir in the beaker glass that has been coated with aluminum foil. After stir process had been done, let stand one night to get a maximum extraction. Sensor design is printed on the paper sticker and sticking on TCO glass to help pattern mold deposition process of TiO_2 paste. TiO_2 paste required solution made from 1.5 gram of polyvinyl alcohol and 15 mL of H_2O which is stirred using a magnetic stir for 30 minutes with a temperature of 40°C to the solution thickens [13]. A 0.5 gram of powdered TiO_2 is mixed with 7.5ml aqueous then to be a binder and stir to form a TiO_2 paste. The paste of TiO_2 will deposition in spin speed of 1000 rpm. Firing process of TiO_2 in the furnace on a temperature of 250 °C for 10 minutes and soaking process of Annealed-material to the extracted Chlorophyte dye for 30 minutes.

3.2. Sensor Measurement Analysis

The chlorophyll absorbance was investigated by spectrophotometer UV-VIS 1800 at the wavelength of 300-800 nm. SEM (Scanning Electron Microscope) is used to observe TiO_2-coated TCO glass morphology. Fabricated sensors are characterized according to the electrical parameters of voltage and current towards light illumination from the light source. This natural dye-based photodetector performance has been analyzed to obtain linearity, sensitivity, uncertainty error and other electrical transient response characteristics. Analysis of the calculation of the sensitivity of the sensor is conducted by observation at how the value of the voltage generated from the data retrieval output voltage sensor that is done repeatedly to variations of the sensors input. Sensitivity indicates how far the sensitivity of the sensor against the quantity measured. Sensitivity is often also expressed with numbers that show the change in output than input change units. Linearity of the sensor also affects the sensitivity of the sensor. The sensor's sensitivity is indicated in (13).

$$S = a + bs \quad (13)$$

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where:
S: sensor output signal
a: the sensor output at current input zero
b: sensor sensitivity

The sensitivity of the sensor at any point in the input is expressed by equation (14).

$$b = \frac{dS(s_0)}{\Delta s} \quad (14)$$

where:
b : Transfer function of the derivative towards s
s : Certain input values

4. Results and Discussion

4.1. Absorbance Spectra and Layer Morphology

The absorbance spectra measurement of the extracted dye from green algae is shown in Figure 3. This result shows that the dye sample with different concentrations has the variation with wavelength of 490-680 nm. The highest visible light absorbance was achieved by the concentration of variations sample 3 with the ratio of 6:5 (m:v) than any other solution. The morphology of deposited TiO_2 layer was investigated by SEM with front view image observation. This image indicates micro-nano porous TiO_2 morphology under 10 µm scale associated with dye molecule. The morphological deposited TiO_2 layer is shown in Figure 4.

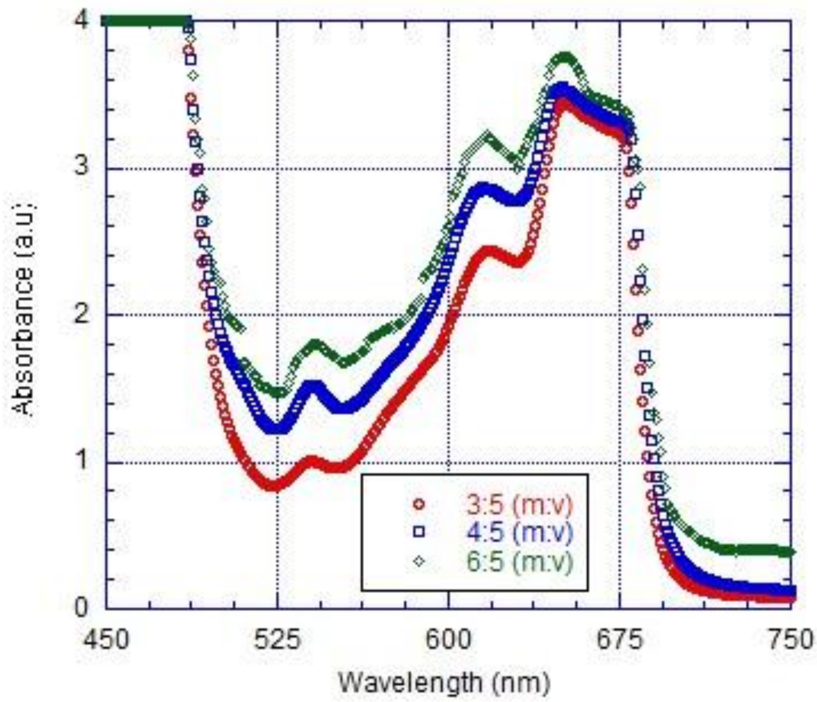

Figure 3. The absorbance spectra of dye from chlorophyte

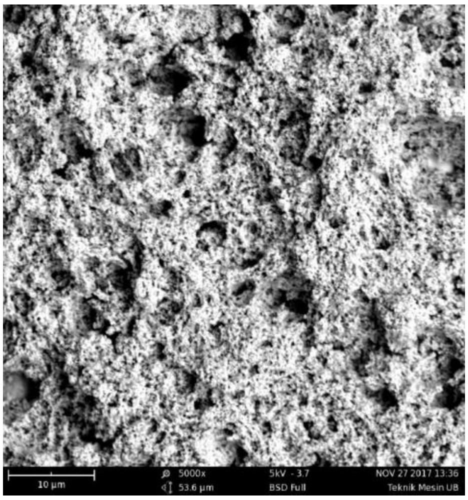

Figure 4. SEM image of TiO2 layer morphology by 5000x Magnification

4.2. Sensor Electrical Output

Table 1 shows the voltage and current output of the sensor while the measurement under illuminance of 500-30,000 lux. Based on the data, if the illuminance in photodetector test will be increased, the output voltage of photodetector will increase. The higher illuminance that given to photodetector, the temperature at the time of testing is also increasing. The higher ratio concentration sample that has been made, the output voltage in the photodetector will increase too. Its shown in sample 3 that the value of output voltage is bigger than others. Based on the data, the greater the illuminance to be measured to photodetector so the resulting output voltage of photodetector will increase. The higher illuminance that given to photodetector, the temperature at the time of testing is also increasing. The higher ratio concentration sample that has been made, the output voltage in the photodetector was also increase.

Table 1. The Influence of Illuminance Variations towards Output Voltage

Design	Illuminance (lux)	Voltage (mV)	Current (μA)
Sample 1 (3:5)	500	275.2	9.2
	1000	299.1	13.4
	1500	312.5	14.6
	1800	319.3	15.2
	2700	326.6	15.4
	3000	338.4	16.1
Sample 2 (4:5)	500	435.8	8.4
	1000	469.6	14.3
	1500	481	21.5
	1800	483.8	31.3
	2700	489.4	37.7
	3000	490	35.5
Sample 3 (6:5)	500	577.4	8.9
	1000	614.6	30.18
	1500	618.2	42.28
	1800	619.8	73.36
	2700	624	78.46
	3000	624.4	48.68

4.3. Sensor Parameter Analysis

Analysis of calculation of photodetector sensitivity is conducted by identifying at some of the values of voltage and current that results from testing the photodetector. This analysis is used in the calculation of the two measurements data for each voltage or current testing results. Sensitivity analysis of the photodetector following based on voltage and current outputs are shown in Table 2 and Table 3. Based on Table 2, sensitivity sensor based on average output voltage that has the biggest relative uncertainty shown in sample 2 and the best uncertainty shown in sample 3. Then the sample 1 has the highest linearity based on the average output voltage.

Table 2. Voltage-Based Sensitivity, Uncertainty, and Linearity Analysis of the optical sensor

Sensor	Sensitivity (mV/lux)	Uncertainty (%)	Det. Coef.
1 (3:5)	0.0034	1.844	0.9946
2 (4:5)	14.272	1.601	0.9633
3 (6:5)	10.875	0.387	0.9794

Table 3. Current-Based Sensitivity, Uncertainty, and Linearity Analysis of the optical sensor

Sensor	Sensitivity (µA/lux)	Uncertainty (%)	Det. Coef.
1 (3:5)	1.5494	0.881	0.9757
2 (4:5)	0.0010	0.720	0.9878
3 (6:5)	0.0024	0.481	0.8275

The time response of the sensor was achieved by 10 s. Figure 5 shows the time response of the sensor in first-order characteristic. Based on Table 3, the photodetector based on average output current that has the biggest relative uncertainty shown in sample 1 and the best uncertainty shown in sample 3. Based on sensor sensitivity, the output voltage characteristic has higher sensitivity propose to be used as electrical parameter output. The voltage output profile is shown in Figure 6. According to the relative uncertainty analysis, the characteristic of voltage output has also indicated the significant result with the variation of 6:5 (m:v) concentration. The result of relative uncertainty is shown in Figure 7.

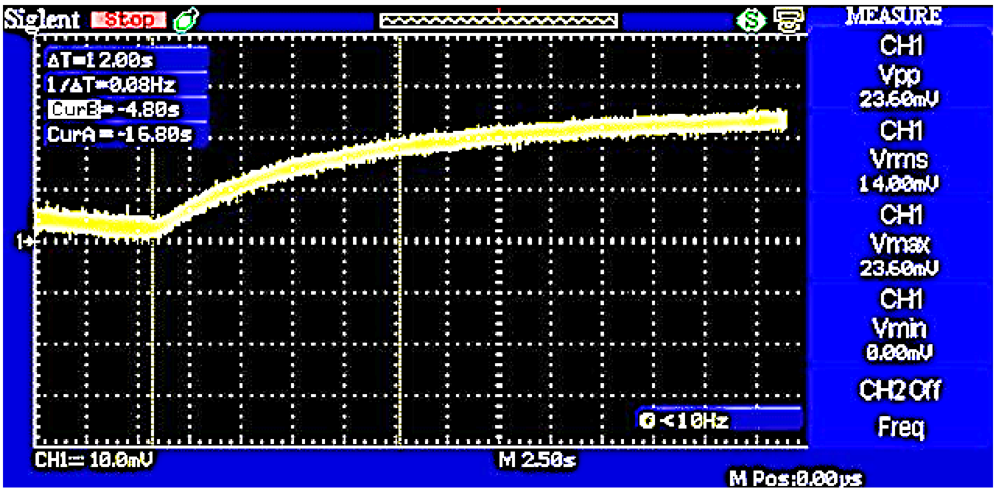

Figure 5. Time response of the sensor on the oscilloscope view

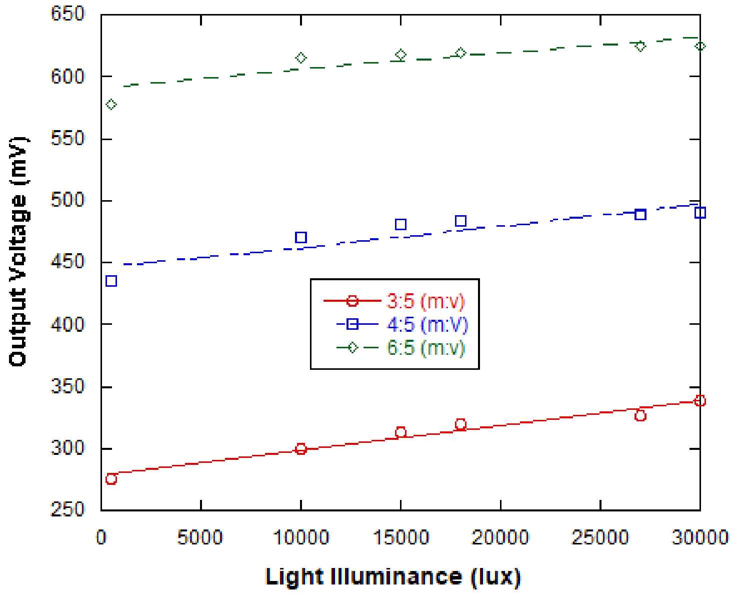

Figure 6. Sensor characteristic profile based on the output voltage

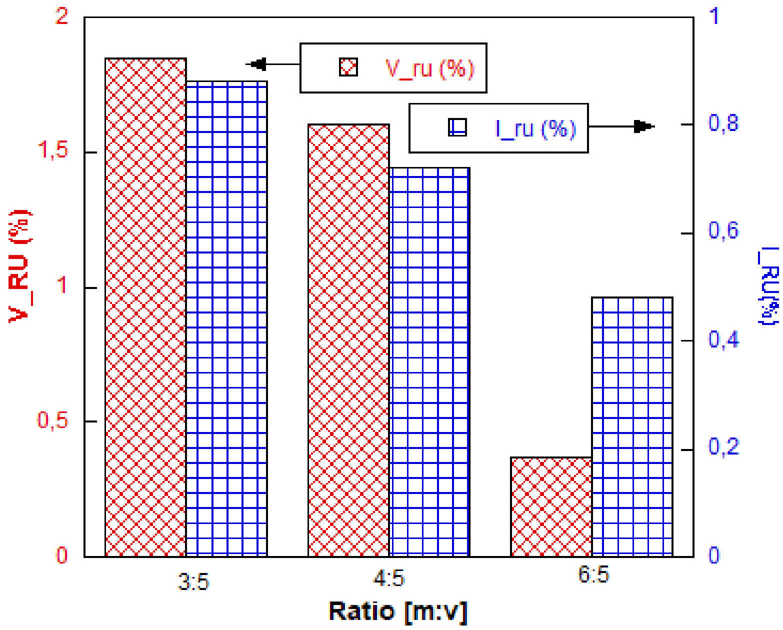

Figure 7. Relative Uncertainty comparison between voltage and current.

5. Conclusion

According to the experimental method and measured photodetector, conclusions of this paper are the absorbance at the wavelength range of 500-675 nm; sample 6:5 has the highest absorption than other samples. When the illuminance increase, output voltage and output current was decrease, and the higher concentration would be given to photodetector, then the output voltage and current became higher. The photodetector that has the highest sensitivity based on output voltage was obtained in sample 4:5, but the highest sensitivity based on output current would be shown in sample 3:5. Based on analysis, sample 4:5 has the highest linearity based on average output current. The photodetector that has the best or smallest uncertainty based on the output voltage and output current is indicated in sample 6:5 (m:v).

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