Performance Degradation Model of Dye-Sensitized Solar Cell (DSSC) Using Dye Extracted from Red Dragon Fruit’s Flesh

Natalia Burhan¹ and Henri P. Uranus²,*

¹,²Dept. of Electrical Eng., Univ. Pelita Harapan, Jl. M. H. Thamrin Blvd. 1100, Tangerang 15811, Indonesia

*Corresponding author: henri.uranus@uph.edu

Abstract. This paper reports on the fabrication and characterization of dye-sensitized solar cell (DSSC) which utilizes dye extracted from local red dragon fruit’s flesh. The DSSC was hand-made using doctor blade method on single-sided ITO-coated TCO glass with iodine solution as the liquid charge transporter and dye infiltrated mesoporous layer made from paste of TiO₂ nanoparticles powder and acetic acid. The fabricated samples were tested using an own-made solar simulator with 85 W 12 V halogen light source and measured for I-V curve using a home-made Arduino-based automated I-V measurement tool. The experiments gave best results for DSSC which use a paste composed of 1 gr of TiO₂ nanoparticle powder and 3.2 ml of 15% acetic acid soaked in dye for 90 mins. The results show that a cell of 21 mm x 21 mm has open circuit voltage (V_{oc}) of 459.28 mV, short circuit current (I_{sc}) of 10.14 μA, fill factor (FF) of 55.39% and conversion efficiency (\eta) at maximum power point (MPP) of 0.0088% at 30 minutes post assembling under exposure to 66.7 W/m² irradiation. The DSSC degraded over time and fitted well to a two-parameter model equation. Compared to similar cell fabricated using dye taken from blackberry fruit, which exhibited \eta = 0.0133%, the cell with dye of red dragon fruit’s performance is worse.

1. Introduction

Dye-sensitized solar cell (DSSC) [1] is a solar cell that uses the principle of photosynthesis to harvest solar energy. Although the efficiency of DSSC is still below silicon solar cell [2], it is still interesting, due to its easy fabrication method that does not need sophisticated tools, so it can be fabricated by hand in simple chemistry lab., and has the possibility to use organic dyes from local fruits or leaves. Indonesia is a country with rich bio-diversity, whereas many fruits or leaves with unique dyes need exploration for their potential to be used in DSSC.

Following our previous work that used dye taken from blackberry fruit [3], it is interesting to check the performance of other kinds of dyes, e.g. the one extracted from red dragon fruit (hylocereus costaricensis). Red dragon fruit’s skin [4], [5] and flesh [6], [7] were known to contain anthocyanin suitable as sensitizer for DSSC. Unsealed DSSC with liquid electron transporter and fabricated using simple fabrication method, has inevitable performance degradation. In this work, the performance degradation of DSSC with dye extracted from red dragon fruit’s flesh made using simple fabrication method was investigated using own-made solar simulator and home-made Arduino-based fast automated I-V curve measurement set-up. The solar cell device parameters were extracted from the measured data using curve fitting to a simplified one-diode model. The performance degradation was
then modeled using a two-parameter model. Comparison to DSSC made using dye extracted from blackberry fruit is also reported.

2. Samples Preparation

Six samples were fabricated using various fabrication parameters i.e. dye soaking durations and concentrations of TiO$_2$ – acetic acid paste as shown in Table 1. The samples were prepared following simple fabrication scheme shown in Fig. 1.

| Sample | TiO$_2$ paste concentration | Dye soaking duration |
|--------|-----------------------------|----------------------|
| A      | 1 gr TiO$_2$ +             | 30 min               |
| B      | 3.2 ml 15% acetic acid     | 60 min               |
| C      |                             | 90 min               |
| D      | 2 gr TiO$_2$ +             | 30 min               |
| E      | 3.2 ml 15% acetic acid     | 60 min               |
| F      |                             | 90 min               |

Table 1. The samples prepared in the experiments

![Diagram of sample preparation](image1.png)

Figure 1. The samples’ preparation scheme.

![Images of sample preparation](image2.png)

Figure 2. Electrodes preparation: (a) the use of Scotch tape as mask, (b) the electrode with TiO$_2$ mesoporous layer infiltrated by dye extracted from red dragon fruit’s flesh, and (c) the carbon coated counter electrode.

The TiO$_2$ paste was prepared by mixing TiO$_2$ nanoparticle powder of 22 nm size from Sigma Aldrich 798495 and 3.2 ml of acetic acid. The paste was coated on the conductive side of 25 mm X 25 mm commercial single-sided ITO-coated TCO glasses purchased from Kintec [8] using doctor blade [9].
method by using Scotch tape as mask on the three edges, resulting in 21 mm X 21 mm of coated area as shown in Fig. 2(a). The TCO glasses were dried in room temperature for 15 minutes, then heated on a hot plate of 450 °C for 30 minutes to obtain mesoporous layer of TiO$_2$ of 2.54 µm and 10.976 µm thickness for paste prepared with 1 gr TiO$_2$ solved into 3.2 ml of 15% acetic acid and 2 gr TiO$_2$ solved into 3.2 ml of 15% acetic acid, respectively, as shown in microscopic measured results in Fig. 3.

![Figure 3. Microscopic picture of the TiO$_2$ layer for sample made with (a) paste prepared with 1 gr TiO$_2$ solved into 3.2 ml of 15% acetic acid and (b) 2 gr TiO$_2$ solved into 3.2 ml of 15% acetic acid, respectively.](image)

For electrode preparation, the dye was extracted from the flesh of the red dragon fruit and used to infiltrate the TiO$_2$ mesoporous layer by soaking the coated glass into the dye solution for certain amount of durations as given in Table 1. Fig. 2(b) shows a dye-infiltrated electrode. For counter electrode preparation, a plain TCO glass was coated with carbon by heating the conductive side using candle with result shown in Fig. 2(c).

The electrolyte solution was prepared following the steps given by Tanihaha et al [3] by solving 830 mg of potassium iodide (KI) powder into 5 ml polyethylene glycol and mixed it with a solution of 126 mg of iodine (I$_2$) in 5 ml of polyethylene glycol.

The samples were assembled by putting a drop (~50µl) of electrolyte solution onto the TiO$_2$ coated side, arrange the side face to face with the carbon coated side of counter electrode, slide them slightly so that the uncoated part of the TCO layer of both electrodes become accessible for later measurement and clamp them with paper binder clips as shown in Fig. 4. Scotch tape of 100 µm thick at two edges of the carbon electrode behaves as the spacer between the two electrodes.

![Figure 4. Cell assembly: (a) the electrode arrangement, and (b) a sample of assembled DDSC.](image)
3. Measurements and Model

The optical – electrical conversion and electrical characteristics of the samples were measured using a home-made Arduino-based automated I-V curve measurement set-up with samples put inside an own-made simple solar simulator as shown in Fig. 5(a). The own-made solar simulator with 85 W 12 V halogen light source and white PMMA light diffuser plate had been reported in earlier publication [10]. In this set-up, two servo motors were used to turn two variable resistors to vary the load, one for coarse adjustment, and the other for fine adjustment while the Arduino measured and logged the current and voltage out of the cell.

![Simplified Solar Cell Equivalent Circuit](image)

**Figure 5.** (a) The solar cell characterization measurement set-up and (b) the simplified one-diode model of the solar cell under the measurement set-up.

![Measured Points and Best Fitted I-V Curve](image)

**Figure 6.** The measured points and the best fitted I-V curve of sample C for various duration after the cell assembling.
A simplified one-diode model [11] of the solar cell and the variable load of the measurement set-up is shown in Fig. 5(b), where the internal series and shunt resistances of the cell are ignored. This model gives relation between current and voltage of the solar cell of

\[ I(V) = I_L - I_0 \left( \frac{V}{e^{\frac{V}{nV_T}} - 1} \right) \]  \hspace{1cm} (1)

with \( I, V, I_L, I_0, m, \) and \( V_T \) are the solar cell current to the load, the solar cell voltage, the solar cell photo current, the dark current, the diode ideality factor, and the thermal voltage, respectively. The measurement results were then curve-fitted to this model equation to obtain the best-fitted \( I_L, I_0, \) and \( m. \) Fig. 6 shows the measured points and best-fitted \( I-V \) curve for sample C for various time after cell assembly. Iterative method using nonlinear least square has been used for the curve fitting. The rms of errors of the curve fitting are 0.2 \( \mu A, 0.17 \mu A, 0.19 \mu A, 0.13 \mu A, 0.13 \mu A, 0.14 \mu A, 0.13 \mu A, \) and 0.12 \( \mu A \) for dataset of minute 5, 7, 9, 15, 20, 25, 30, and 60 after cell assembling, respectively. Fig. 6 also shows measurement results of a cell fabricated without dye. Comparing the cells with dye and without dye confirms that the electricity generated in the cells with dye indeed came from optical to electrical energy conversion.

Using the best-fitted device parameters, the open-circuit voltage \( V_{OC} \) and short-circuit current \( I_{SC} \) are extracted using

\[ V_{OC} = mV_T \ln \left( 1 + \frac{I_L}{I_0} \right) \]

\[ I_{SC} = I_L. \]

The power produced by the solar panel is obtained by multiplying Eq. (1) with \( V \) which gives

\[ P = I_L V - I_0 \left( e^{\frac{V}{nV_T}} - 1 \right) V. \]  \hspace{1cm} (2)

The MPP (maximum power point) is obtained by taking the maxima of Eq. (2) and solved the resulted equation numerically to get maximum power point voltage \( V_m \) and current \( I_m. \) The fill factor then can be calculated as

\[ FF = V_m I_m / V_{OC} I_{SC}. \]

By measuring the optical intensity \( I_{op} \) using solar power meter TES1333R, the optical power \( P_{op} \) can be obtained through

\[ P_{op} = I_{op} A_{sample} \]

where \( A_{sample} \) is the area of the solar cell. The cell’s maximum efficiency can then be calculated through

\[ \eta = V_m I_m / P_{op}. \]

**Table 2.** The cell electrical characteristics extracted through curve-fitting of measured points to one-diode model for sample C for various times after the cell assembly.

| Time after assembly (min) | \( V_{OC} \) (mV) | \( I_{SC} \) (\( \mu A \)) | \( V_m \) (mV) | \( I_m \) (\( \mu A \)) | \( FF \) (%) | \( \eta \) (%) |
|---------------------------|-------------------|-----------------|----------------|----------------|------------|------------|
| 5                         | 529.284           | 17.75           | 385.063        | 14.61          | 59.87      | 0.0191     |
| 7                         | 517.259           | 13.2            | 384.293        | 11.13          | 62.62      | 0.0145     |
| 9                         | 507.987           | 11.98           | 376.606        | 10.07          | 62.34      | 0.0129     |
| 15                        | 486.376           | 10.63           | 359.41         | 8.91           | 61.91      | 0.0109     |
| 20                        | 475.129           | 10.23           | 343.625        | 8.36           | 59.09      | 0.0098     |
| 25                        | 465.424           | 10.09           | 332.561        | 8.12           | 57.52      | 0.0092     |
| 30                        | 459.275           | 10.14           | 322.785        | 7.99           | 55.39      | 0.0088     |
| 60                        | 429.128           | 9.951           | 299.111        | 7.76           | 54.33      | 0.0079     |

**4. Performance Degradation**

Table 2 shows the measured and best-fitted device parameters for sample C which appeared to be the best sample. The table clearly shows that the device has rather low efficiency, which we believe comes from the imperfect simple fabrication method used in this work. The results show that a cell of 21 mm
x 21 mm has open circuit voltage (\(V_{oc}\)) of 459.28 mV, short circuit current (\(I_{sc}\)) of 10.14 \(\mu\)A, fill factor (\(FF\)) of 55.39% and efficiency (\(\eta\)) at maximum power point (MPP) of 0.0088% at 30 mins after assembling under 66.7 W/m² irradiation inside the solar simulator. The results also show that the cell has inevitable performance degradation.

To study the performance degradation of the cells, a two-parameter model of

\[
\eta(t) = A e^{-\tau_{\eta1}} + B e^{-\tau_{\eta2}}
\]

was used for the efficiency degradation. This model turned out to fit well, which indicates that the performance degradation comes from more than one factors, e.g. the electrolyte evaporation, the changing of the chemical properties of the electrolyte, etc. Fig. 7 shows the performance degradation of all samples. The figure shows that at 30 min after the cell assembly, the cells’ performance was already stable. Table 3 shows the efficiency of the cells obtained from Fig. 7 at 30 minutes after assembly, which shows that sample C was the best performed cell.

![Figure 7](image)

**Figure 7.** The measured performance degradation of the fabricated cells and their best-fitted curve to a two-parameter model.

**Table 3.** Efficiency of fabricated cells at 30 minutes after the cell assembly where the performance reach stability.

| Sample name | Cell efficiency (%) |
|-------------|---------------------|
| A           | 0.0079              |
| B           | 0.0083              |
| C           | 0.0088              |
| D           | 0.0055              |
| E           | 0.0073              |
| F           | 0.0075              |

Similar experiments were also performed on DSSC with dye extracted from the flesh of blackberry fruit, using best performed parameters given by Tanihaha et al [3], i.e. with paste composition of 2 gr of TiO₂ solved in 3.2 ml of 15% acetic acid with dye soaking duration of 30 minutes. Table 4 shows the cell’s electrical parameters.

Fig. 8 shows comparison between the I-V curve of sample C and the cell with dye extracted from blackberry fruit at 30 minutes after assembly. The results show that the cell with blackberry dye has higher \(I_{sc}\) but slightly lower \(V_{oc}\). Fig. 9 shows the performance degradation curves of both cells which shows that although the cell with dragon fruit dye performs better just after assembly, it degrades faster, and hence stabilized at lower efficiency than the cell with blackberry dye. This difference in performance
comes from the different physical (e.g. absorption spectrum) and chemical (e.g. hydrophobicity of the dye, matching between the molecular energy level of the dye to the energy level of the TiO₂) properties of the dyes. However, such investigations are beyond the scope of this paper. These results suggest that further study is required in the future to study the dye and improve the performance of DSSC cell with dye taken from the red dragon fruit’s flesh.

Table 4. The cell’s electrical characteristics of DSSC made using dye extracted from the flesh of blackberry fruit with fabrication parameters taken from Tanihaha et al [3] extracted through curve-fitting of measured points to one-diode model for various times after the cell assembly.

| Time after assembly (min) | V_{OC} (mV) | I_{SC} (µA) | V_{m} (mV) | I_{m} (µA) | FF (%) | η (%) |
|--------------------------|-------------|-------------|------------|------------|--------|-------|
| 6                        | 428.875     | 18.48       | 316.848    | 15.48      | 61.88  | 0.0167|
| 8                        | 430.966     | 18.54       | 316.71     | 15.44      | 61.19  | 0.0166|
| 14                       | 421.492     | 14.46       | 315.852    | 12.30      | 63.75  | 0.0132|
| 16                       | 417.239     | 15.87       | 311.017    | 13.42      | 63.05  | 0.0142|
| 20                       | 411.169     | 14.4        | 313.538    | 12.47      | 66.03  | 0.0133|
| 22                       | 413.839     | 14.85       | 307.756    | 12.53      | 62.74  | 0.0131|
| 24                       | 404.15      | 13.6        | 313.027    | 11.95      | 68.07  | 0.0127|
| 26                       | 410.923     | 15.91       | 302.389    | 13.27      | 61.36  | 0.0136|
| 28                       | 409.19      | 14.46       | 308.85     | 12.39      | 64.69  | 0.0130|
| 30                       | 407.118     | 14.87       | 307.557    | 12.76      | 64.81  | 0.0133|
| 60                       | 398.576     | 14.81       | 299.244    | 12.62      | 63.99  | 0.0128|

Figure 8. The comparison of I-V curve of sample C to the one of cell with blackberry dye at 30 min after assembly.

Figure 9. The comparison of performance degradation of the sample C to the cell with blackberry dye. The rms of errors of the curve fitting are 0.0003% and 0.0004% for the red dragon fruit and blackberry data, respectively.

5. Conclusions

Several dye-sensitized solar cells using dye extracted from the flesh of red dragon fruit were fabricated and investigated for their performance degradation. The results show that a two-parameter model fit well to the measured results indicating that the degradation has more than one causes. The sample were also compared to a similar cell fabricated using dye extracted from blackberry fruit. The results show that cell using dye from blackberry degraded slower, showed higher short circuit current, and stabilized...
at higher efficiency than the one with dye from red dragon fruit. This experiment suggests that further research is required to improve the performance of DSSC with dye from red dragon fruit’s flesh.

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