Abstract

An organic material is proposed as a sustainable sensitizer and a replacement for the synthetic sensitizer in a dye-sensitized solar cell technology. Using the liquid extract from the leaf of a plant called Mimosa pudica (M. pudica) as a sensitizer, the performance characteristics of the extract of M. pudica are investigated. The photo-anode of each of the solar cell sample is passivated with a self-assembly monolayer (SAM) from a set of four materials, including alumina, formic acid, gelatine, and oxidized starch. Three sets of five samples of an M. pudica-based solar cell are produced, with the fifth sample used as the control experiment. Each of the solar cell samples has an active area of 0.3848cm². A two-dimensional finite volume method (FVM) is used to model the transport of ions within the monolayer of the solar cell. The performance of the experimentally fabricated solar cells compares qualitatively with the ones obtained from the literature and the simulated solar cells. The highest efficiency of 3% is obtained from the use of the extract as a sensitizer. It is anticipated that the comparison of the performance characteristics with further research on the concentration of the extract of M. pudica will enhance the development of a reliable and competitive organic solar cell. It is also recommended that further research should be carried out on the concentration of the extract and electrolyte used in this study for a possible improved performance of the cell.

1. Introduction

The discovery and innovation for new materials are probably not catching up with the growing demand for energy, especially with the increasing world population. Renewable energy, which is capable of being an alternative source of energy, offers a significant potential for sustainable development in the world. The fact that the consumption of fossil fuel is closely linked to global warming is increasing the quest for the development of alternative power generation. However, the major challenge in the development of the third-generation solar cell is the slow pace of research advances in the field of energy conversion. While attempting to proffer a solution to this challenge, efficient transport of the holes and poles within the microcopes of the new organic material for solar cell production represents an emerging challenge. Lee et al.1 reported that a conventional solar cell module typically converts about 15% of incident sunlight into electricity, whereas the high level of purity and temperature requirements represent a mismatch between the efficiency of the solar cell and its cost-effectiveness. Grätzel2 introduced the concept of the dye-sensitized solar cell (DSSC) to serve as a replacement for the silicon-based solar cells.2-4 The introduction of the DSSC capabilities toward the development of innovative technology is being explored at the nanoscale level to provide alternative solar photovoltaic technology. While new concepts toward the discovery of sustainable...
solar cell material are developing, the use of nanocrystalline TiO$_2$ for the production of a dye-sensitized solar cell is generating encouraging research attention. However, the use of ruthenium-based complexes as the dye has been predominant for the production of the dye-sensitized solar cell.

Since ruthenium is not available locally, the discovery of new solar cell–like polymers and molecular dyes suggests the possibility of developing a less expensive, environmentally friendly, and sustainable solar cell from organic materials. The introduction of a locally available alternative sensitizer will be a significant discovery and a step forward in promoting sustainability. Samejima and Sibaoka investigated the photosynthetic energy transport response of the leaf of *Mimosa pudica* (i.e., *M. pudica* L., an organic plant, locally known as “Touch me not”). They reported the successful measurement of chloride and potassium efflux on the primary pulvina of *M. pudica* with microelectrodes during a seismonic reaction. Kumon and Suda observed the ionic fluxes from pulvinal cells during the rapid movement of *M. pudica* leaf. Apart from the anticipated electric conductivity of the fluxes, the implications of these stimulations have been investigated, including light transduction and electric conductivity. Recently, the photosensitivity of this organic material was explored by a team of researchers from the University of Lagos, Nigeria, Nsukka, Nigeria. Alonge et al. simulated the thermal diffusion characteristics in *M. pudica* solar cell with source term and without source term. Furthermore, Ogedengbe et al. proposed the possibility of embedding *M. pudica* between two metallic conductors in order to achieve low-cost energy, due to the ease of manufacture, light weight, and compatibility with flexible substrates.

This article proposes an alternative to the ruthenium complex by exploring the potential of a locally available plant leaf extract (*M. pudica* extract). Dividing the presentation into three major parts, section 2 focuses on the experimental production of the laboratory solar cell, including the surface treatment of the photo-anode and the process of sensitizing the cell with the extract. Section 3 addresses the numerical method and simulation of excess carriers within the micropores of the solar cell. Section 4 presents the discussion of the comparison between the experimental approach and the numerical simulation results.

## 2. Experimental materials and measurement

The materials used for the experimental work includes fluorine tin doped oxide (FTO) transparent conducting (TC) glass with the following specifications: 2.5 cm × 2.5 cm in dimension, with nominal film thickness of 6 microns, resistivity of 13 ohm/sq., and visible transmittance of 85%, tri-iodide (electrolyte), *M. pudica* (dye) sensitizer (processed locally from *M. pudica* leaves at the University of Lagos, Nigeria), titanium dioxide (TiO$_2$), ionized H$_2$O, platinum catalyst, and ethanol. A circular profile for the TC, with a diameter of 0.7 cm and the active area of 0.3848 cm$^2$, is adopted. The method of doctor blading is used to prepare three sets of five cell samples. The process of preparing the working electrode involves a 10 μm deposit of TiO$_2$ nano-crystalline particle on the FTO glass, followed by drying at 100°C before annealing at 450°C for 30 mins. The counter electrode is prepared by depositing a layer of platinum catalyst gel coating onto the FTO transparent conducting glass, dried and annealed at the same processing temperature for the working electrode.

### 2.1 Surface treatment

Out of the three set of five cell samples, one set is used as the control experiment, while the other four sets are treated for porous passivation in order to increase the protection of the deposited nano-crystalline TiO$_2$. A self-assembly monolayer (SAM) technique, where molecular assemblies formed by the spontaneous adsorption of an active surfactant on a solid surface from a liquid or a gas phase, is adopted. Haensch et al. reported the significant attention SAMs have been generated, since its introduction by Sagiv. The importance of SAM cannot be overstressed, because of its wide range of application. It provides an unconstrained surface for bonding purposes and chemisorption.

The SAM technique involves the use of different types of liquid reagents for the enhancement of adsorption. A set of sample is dipped one after the other into a warm liquid reagent with a clean forceps and then allowed to stay in the reagent for 10 secs. On removal from the reagent, it is dipped into distilled water for 10 seconds. This process is repeated four times for each sample in a set, making an approximate process time of 40 secs. The gelatine-based SAM is prepared with 3 g of gelatine added to 50 ml of distilled water solution for the purpose of passivating the surface of the working electrode. The same procedure is adopted for other SAM samples. For example, formic acid is used as the reagent, instead of gelatine, in the case of formic acid SAM. Being a carbohydrate extract and a product of a locally grown cassava tuber, starch is procured in a local market and oven dried in order to prepare the solution of oxidized starch; 1 g of the dry starch is measured and transferred into a beaker, with a combination of 50 ml sodium hydrochloric (NaHCl) acid and 2 molar sodium hydroxide (NaOH) concentrations. For a clear solution, 75 ml of ethanol is added to the solution for precipitation. A 200 ml of the resulting solution is purifed, using hydrochloric (HCl) acid, as used for the starch-based SAM passivation technique. The SAM-surfaced samples include samples that are treated with

![Figure 1a. Gelatine treated samples.](image-url)
reagents, including alumina, formic acid, gelatine, and oxidized starch.

Figures 1a to 1d represent the treated surfaces of the samples in gelatine, oxidized starch, alumina, and formic acid.

2.2 Sensitization and bonding

The prepared sets of samples are sensitized using the M. pudica extract, by adopting the standard sensitization procedure for dye-sensitized solar cells. The treated and sensitized working electrode is bonded together with a counter electrode, using a binder. An electrolyte is introduced, which contains free ions that behave as an electrically conductive medium. The circuitry setup for the apparatus comprises a computer, data acquisition system (DAS), cell holder, and arc lamps. The internal sweep circuit in the DAS applies either current or voltage, and the measurement circuit measures the other quantity (voltage or current, respectively). The solar simulator provides standard test conditions (STC) for the solar cell. The simulator arc lamp, when switched on, supplies AM1.5 (air mass) spectrum. The light is incident on the solar cell on the alligator clip to generate current and voltage that are measured with the help of DAS. The test environment is maintained at 25°C. The dark measurement of the cell is carried out by placing a black material on the cell to prevent irradiation entering the cell at the same time, while the DAS measures all the parameters required.

The useful wavelength range for this kind of cell is from 190 nm to 640 nm with 1.248 A (absorbance) peak measured, suggesting the restricted solar spectrum for effective utilization of the proposed organic solar cell. Likewise, due to the expected effect of degradation on the performance of sensitizer, under a prolonged exposure to sunlight, further investigation on the scale of aging and the proposed maintenance mechanism is ongoing. It is anticipated that certain study of the electrochemical impedance (EIS) and Fourier transform infrared (FTIR) spectroscopy can provide useful information about the aging phenomenon.

3. Mass transport model and simulation

Accurate characterization of the transport of excess carriers through the micropores of the proposed organic solar cell material requires the combination of both laboratory experiments and numerical simulations. Advances toward the development of comprehensive real models that could contribute to the optimization of dye-sensitized solar cells have driven the application of theoretical models for the current-voltage (IV) behavior of the microporous semiconductor film in photochemical cells. Sodergren et al. assumed diffusion is the sole means by which carriers, specifically electrons in the nanocrystalline TiO₂ film, are transported. This assumption enabled the use of free parameters to generate the current-voltage (IV) curve with the theoretical results. In the electrolytes, the mass transport of carriers takes place by the process of diffusion. It depends largely on the ions’ coefficient of diffusion and the structure of the microporous layer.
Also the viscosity of the electrolytes contributes to the mass transport of carriers. Gagliardi et al. modeled dye-sensitized solar cell (DSSC) using the finite element method. They presented an electrical model of the cell with the measured current-voltage curve while explaining the role of different parameters involved in the physics of the conversion of light, including the estimated efficiency spectrum for standard DSSC. Most of the previous efforts in this field have failed to present a complete model for the entire device over a general domain, comprising the effects of different SAM. A two-dimensional finite volume method for the formulation of the transport of the excess carriers within the micropores of the organic solar cell is hereby presented.

Figure 2 represents the schematic of the working principle of the M. pudica (dye) sensitized solar cell. Like any other kind of cell, DSSC also can generate carriers, transport the carriers to the external load at a higher voltage, and bring back the carrier in the cell at a very low voltage. The major advantage of DSSC is that the electron—hole pair is generated in the dye by photo-excitation. The split in between the micropores is the excess concentration of the electrons generated as a result of illumination at positions x and y within the film measured from the TiO$_2$/fluorine titanium oxide glass interface. It is assumed that the electrons are under steady condition. This is why the effect of trapping and de-trapping electrons is not considered in the model equation of transport, recombination, and generation of electrons within the TiO$_2$ film.

3.1 Discretization of the governing equation

The model equation is discretized using the finite volume method. It is assumed that the electrons are in steady state. In order to obtain a steady state transport, a transient term is numerically approximated. A two-dimensional computational stencil for a finite volume formulation of the transport of vector and scalar field variables in the active area of the cell is represented by Figure 3.

Let $n$ in the model equation be represented with $n$. This is because of the sign notation of computational fluid dynamics (CFD), which would be employed in the following integration in time and space of the control volume domain.

Let

$$D_n = \left( \frac{kT}{q} \right) \mu_n$$

It should be noted that the transient term introduced in equation (1) is for the purpose of obtaining an algebraic equation that could handle both steady and transient condition of the M. pudica (dye) solar cell. The following discretization focuses on the scalar control volume

$$\int_{t_1}^{t_1+dt} \int_{s_1}^{s_1+ds} \int_{c_1}^{c_1+dc} \frac{dn}{dt} \, ds \, dy \, dx = \int_{t_1}^{t_1+dt} \int_{s_1}^{s_1+ds} \int_{c_1}^{c_1+dc} D_n \frac{d^2n}{dx^2} \, ds \, dy \, dx + \int_{t_1}^{t_1+dt} \int_{s_1}^{s_1+ds} \int_{c_1}^{c_1+dc} D_n \frac{d^2n}{dy^2} \, ds \, dy \, dx + \int_{t_1}^{t_1+dt} \int_{s_1}^{s_1+ds} \int_{c_1}^{c_1+dc} \frac{dn}{dt} \, ds \, dy \, dx$$

where
\[ S = \frac{(n(x) - n_a)}{\tau_n} + \frac{(n(y) - n_a)}{\tau_n} + G \] (4)

\[ \frac{(C_p - C_{p_0})}{\Delta t} \Delta x \Delta y \]

\[ = \left( D_n \frac{\partial C}{\partial x} \right)_s \Delta y - \left( D_n \frac{\partial C}{\partial x} \right)_w \Delta x + \left( D_n \frac{\partial C}{\partial y} \right)_n \Delta x \Delta y \] (5)

\[ \frac{(C_p - C_{p_0})}{\Delta t} \Delta x \Delta y = \left[ \frac{D_n}{\partial x} (C_E - C_p) \Delta y - \frac{D_n}{\partial x} (C_W - C_p) \Delta y \right] \]

\[ + \left[ \frac{D_n}{\partial x} (C_N - C_p) \Delta x - \frac{D_n}{\partial x} (C_S - C_p) \Delta x \right] \Delta x \Delta y \] (6)

Employing mathematical approximations, rearranging, and making substitutions to equation (6), the algebraic equation for finite volume computation becomes

\[ a_p C_p = a_w C_w + a_c C_c + a_s C_s + a_N C_N + b_1 \] (7)

where

\[ a_p = R_c \] (8)
\[ a_w = R_w \] (9)
\[ a_s = R_{c_1} \] (10)
\[ a_N = R_n \] (11)
\[ a_p = R_p + R_w + R_n + R_c \] (12)
\[ b_1 = S \Delta x \Delta y + a_{p_0} \] (13)
\[ c_p = \frac{C_p}{\Delta t} \Delta x \Delta y \] (14)

Table 1 presents the data extracted from the literature and used for calculating the external parameter using the modeled electrons that have the highest value of electrons per cm. The active area used is the one measured using the four-point probe profiler from the experiment carried out.

In calculating the internal parameters, the current-voltage equation is used for the calculation. The solution to Eq. (1), subject to the internal parameters, yields the following relationship between the current density and voltage:

\[ I_{Total} = qA \left( \frac{D_{con}}{L_n} n_{p0} + \frac{D_{cop}}{L_p} n_{p0} \right) \left( e^{V/kT} - 1 \right) - qAG(L_n + L_p + W) \] (15)

4. Results and discussion

The three sets of the five samples of the cell fabricated are measured under one sun (AM1.5). Figure 4 represents the performance of the three control cells measured.

Table 1. Cell parameters used for calculation.

| Parameter | Value          |
|-----------|----------------|
| \( D_p \) | 0.00033 cm²/s  |
| \( \tau_p \) | 20μs          |
| \( D_n \) | 0.00072 cm²/s  |
| \( \tau_n \) | 50μs          |
| \( G \)   | 1.6e+16        |
| \( q \)   | 1.6e-16        |
| \( A \)   | 0.3848 cm²     |

Figure 4. Performance of control cells.

As earlier mentioned, the photo-anode surfaces are treated with different materials. Figure 5 represents the performance of the alumina modified cell surface. The performance of the cells in terms of increase in current differentiate the three samples; Figure 5 shows great improvement from the first cell to the third cell of the alumina modified cells because of the increase in current. This increase in current appears to be due to certain transport phenomena, including an increase in free electrons that crossed to the conduction band of the cell, reduction in the resistance to the flow of electrons, and reduction in the rate of recombination of electrons and holes, resulting in the increase in the lifetime of electrons.

The next set of cells subjected to measurement includes those cells that are modified with formic acid, and their performances are represented in Figure 6.

The modification of the cell surface with gelatine shows no significant changes as clearly seen in Figure 7. This implies that the rate of mobility of the electrons among the three cells.
exhibits insignificant change, and the resistance to the flow of electrons has not enabled the expected increase in flow that could lead to improvement in the current flow. It implies that the rate of recombination remains almost the same in the three cells.

Investigation of the effects of passivation of the photo-anode represents a significant contribution to this work. The use of starch, being a locally available material, appears novel. Figure 8 represents the performance of the oxidized starch modified cells. In all the three cells (cell1-cell3), there is not much variation in the current density of the cells. This appears to be attributed to the fact that the electron mobility is zero, due to the resistance to the flow of electrons within the cell. The lifetime of the electrons remains the same, while the rate of recombination appears constant.

The averages from the three sets of the five samples are taken, and the performances of the averages are compared. Figure 9 represents the performance of the averages with the modeled performance of the cell. Although solar irradiation varies with time, the irradiance of 1000 W/m² is adopted for the laboratory experiment subject to steady state assumption. The steady state assumption influences the result by generating steady carriers. The transport of the carriers, using the two-dimensional model in Eq. 1, is subject to the cell parameters in Table 1, coupled with the calculation of the short circuit current and open circuit voltage (see Eq. 15).

The parameters for comparing cell performance are tabulated in Table 2. The control cell (CC) has no form of modification on the anode surface of the cell. The fill factor (FF) of the control cell is 35.32%, observed to be the lowest, compared with the FF of the modified cells (i.e., 36.82% for the alumina modified cell (AMC); 42.68% for the formic acid...
modified (FMC); 36.60% for the gelatine modified cell (GMC); and 47.72% for the oxidized starch-modified cells (OSMC) surfaces). It is expected that the modification should increase the absorbance of the extract on the surface of the cell, which is evident in the FF for all the modified cells. Among the modified cells, OSMC has the highest FF of 47.77%, followed by FMC 42.68%. It appears that the high absorbance of the extract on the modified surface contributes significantly to the increase in the FF with modification in the treatment of the surfaces. The extract is well adsorbed as a result of the increase in pores by the reducing agents used for modifying the cell surface. The flow within the pores created by the modification of the cell surface is very important for the improved performance of M. pudica cell, representing the core contribution of this investigation. In terms of the conversion efficiency, CC, AMC, and FMC have the same conversion efficiency. Although these conversion efficiencies are relatively low, they are higher than that of GMC and OSMC.

Using the Kline-McClintock method for the experimental uncertainties in the analysis in Table 2 (see the Appendix for details), the ideal efficiency and the percentage error in experimental measurement are presented in Table 3.

### References

1. Lee, W. J.; Ramasamy, E.; Lee, D. Y.; Song, S. J. Dye-Sensitized Solar Cells: Scale up and Current–Voltage Characterization. Solar Energy Mater. Solar Cells 2007, 91, 1676–1680.
2. Gratzel, M. Photoelectrochemical Cells. Nature 2001, 414, 338–344.
3. Durr, M.; Schmid, A.; Obermaier, M.; Rosselli, S.; Yasuda, A.; Nelles, G. Low-Temperature Fabrication of Dye-Sensitized Solar Cells by Transfer of Composite Porous Layers. Nature 2005, 436, 607–611.
4. Amadelli, R.; Argazzi, R.; Bignozzi, C. A.; Scandola, F. Design of Antenna-Sensitizer Polynuclear Complexes: Sensitization of Titanium Dioxide with [Ru(bpy)2(CN)2]2+ Ru(bpy(COO))222+. J. Am. Chem. Soc. 1990, 112, 7099–7113.
5. Kima, D.-W.; Jeong, Y.-B.; Kim, S.-H.; Lee, D-Y.; Song, J-S. Photovoltaic performance of dye-sensitized solar cell assembled with gel polymer electrolyte. J. Power Sources 2005, 149, 112–116.
6. Galgani, A.; de Maur, M. A.; Gentilini, D.; Di Carlo, A. Modeling of Dye-Sensitized Solar Cells Using a Finite Element Method. J. Comput. Electron. 2009, 8, 398–409.
7. Solanki, C. S. Solar Photovoltaics: Fundamentals, Technologies, and Applications. 2nd edition. Rajkamal Electric Press; New Delhi, 2012.
8. Samejima, M.; Sibako, T. Changes in the Extracellular Ion Concentration in the Main Pulvinus of Mimosa Pudica during Rapid Movement and Recovery. Plant Cell Physiol. 1980, 21, 467–479.
9. Kumon, K.; Suda, K. Ionic Fluxes from Pulvina Cells during the Rapid Movement of Mimosa Pudica L. Plant Cell Physiol. 1984, 25, 975–979.
10. Gosh, R.; Biswas, S.; Roy, S. An Apoprotein from Mimosa Pudica Contains N5, N10-Methenyl Tetrahydrofolate and Is Stimulated by Light. Eur. J. Biochem. 1998, 258, 1009–1013.
11. Nwaogu, J. A.; Okonkwo, W. I.; Unachukwu, G. O. Exploring the Photo-Sensitivities of Mimosa Pudica for Solar Cell Production. 26th European Photovoltaic Solar Energy Conference and Exhibition, 2011, 1DV.1.31, pp 406–410, Hamburg.
12. Alonge, O. J.; Ogedengbe, E. O. B. Heat Transfer and Charge Transport Characterisation of Organic Wafering with Photo-Sensitive Mimosa Pudica Extract. AIAA Collection of Technical Papers, 11th International Energy Conversion Conference (IECEC), San Jose, AIAA, 2013, p 3740.
13. Ogedengbe, E. O. B.; Igbekoyi, O.; Bakare, A.; Alonge, O. J.; Rosen, M. A. Effect of Slip Irreversibility in Organic Thermoelectric
Appendix: Experimental uncertainties

Based on the measured values of the maximum current, maximum voltage, and irradiation, the experimental uncertainty of the efficiency is analyzed using the Kline-McClintock method as follows. The efficiency of the cell is given as

$$\eta = \frac{I_mV_m}{P_{rad}}$$  \hspace{1cm} (A1)

where $I_m$ is the maximum current, $V_m$ is the maximum voltage, and $P_{rad}$ is the measured illumination used. The experimental uncertainty $F$ is

$$\pm F = \pm \eta = \left[ \left( \frac{d\eta}{dV_m} \right)^2 (\epsilon_{V_m})^2 + \left( \frac{d\eta}{dI_m} \right)^2 (\epsilon_{I_m})^2 \right]^{1/2}$$  \hspace{1cm} (A2)

$$\pm F = \left[ \left( \frac{J_m}{P_{rad}} \right)^2 (\epsilon_{V_m})^2 + \left( \frac{V_m}{P_{rad}} \epsilon_{I_m} \right)^2 \right]^{1/2}$$  \hspace{1cm} (A3)

For the control cell (CC) sample, the tolerance for voltage and current are $\epsilon_{V_m} = \pm 0.1V$, $\epsilon_{I_m} = \pm 0.4mA$; while the measured maximum current and maximum voltage are $I_m = 0.84mA$, $V_m = 0.46V$, respectively. The ideal efficiency is $\eta = 0.384$. The percentage error is:

$$\left( \frac{\pm F}{\eta} \right) \times 100 = 0.94\%$$  \hspace{1cm} (A4)

For the alumina modified cell (AMC), $\epsilon_{V_m} = \pm 0.1V$, $\epsilon_{I_m} = \pm 0.4mA$; while the measured maximum current and maximum voltage are $I_m = 0.84mA$, $V_m = 0.46V$, respectively. The ideal efficiency is $\eta = 0.306$. The percentage error is:

$$\left( \frac{\pm F}{\eta} \right) \times 100 = 0.53\%$$  \hspace{1cm} (A5)

For the formic acid modified cell (FMC), $\epsilon_{V_m} = \pm 0.1V$, $\epsilon_{I_m} = \pm 0.4mA$; while the measured maximum current and maximum voltage are $I_m = 0.56mA$, $V_m = 0.32V$, respectively. The ideal efficiency from Eq. (A1) is $\eta = 0.182$. The percentage error is:

$$\left( \frac{\pm F}{\eta} \right) \times 100 = 0.55\%$$  \hspace{1cm} (A6)

For the gelatine modified cell (GMC), $\epsilon_{V_m} = \pm 0.1V$, $\epsilon_{I_m} = \pm 0.4mA$; while the measured maximum current and maximum voltage are $I_m = 0.50mA$, $V_m = 0.42V$, respectively. The ideal efficiency from Eq. (A1) is $\eta = 0.210$. The percentage error is:

$$\left( \frac{\pm F}{\eta} \right) \times 100 = 0.85\%$$  \hspace{1cm} (A7)

For the oxidized starch modified cell (OSMC), $\epsilon_{V_m} = \pm 0.1V$, $\epsilon_{I_m} = \pm 0.4mA$; while the measured maximum current and maximum voltage are $I_m = 0.50mA$, $V_m = 0.42V$, respectively. The ideal efficiency from Eq. (A1) is $\eta = 0.210$. The percentage error is:

$$\left( \frac{\pm F}{\eta} \right) \times 100 = 0.85\%$$  \hspace{1cm} (A8)

The total average percentage error in the efficiency is 0.6%. 

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Material for Photovoltaic Solar Energy Management and Conversion. *Open Fuels Energy Sci.* 1 (paper accepted).

13. Santhaveesuk, S. Synthesis TiO₂ with Doctor Blade Technique for Dye-Sensitized Solar Cell. 6th International Science, Social Sciences, Engineering, and Energy Conference. 17–19 December 2014, Udon, Thailand.

14. Durmaz, F. A Modular Approach to Functional Self-Assembled Monolayers. Doctoral Thesis ETH (2006) No. 16942, Swiss Federal Institute of Technology, Zurich.

15. Haensch, C.; Hoeppener, S.; Schubert, U. S. Chemical Modification of Self-Assembled Silane Based Monolayers by Surface Reactions. *Chem. Soc. Rev.* 2010, 39, 2323–2334.

16. Sagiv, J. Organized Monolayers by Adsorption. I. Formation and Structure of Oleophobic Mixed Monolayers on Solid Surfaces. *J. Amer. Chem. Soc.* 1980, 102, 92–98.

17. Love, J. C.; Wolfe, D. B.; Haasch, R.; Chabinyc, M. L.; Paul, K. E.; Whitesides, G. M.; Nuzzo, R. D. Monolayers and ZnO bonds. *Am. Chem. Soc.* 2004, 125, 2597.

18. Love, J. C.; Lara, A. E.; Jennah, K. K.; Ralph, G. N.; George, M. W. Self-Assembled Monolayers of Thiolates on Metals as a Form of Nanotechnology. *Chem. Rev.* 2005, 105, 1103–1169.

19. Carvalho, A.; Geissler, M.; Schmid, H.; Micel, B.; Delamarche, E.; Langmuir, E. Self-Assembly Monolayer of Metals. *Chem. Soc. Rev.* 2005, 18, 2406.

20. Kramer, R. Z.; Bella, J.; Mayville, P.; Brodsky, B.; Berman, H. M. Gelatine Passivation on Cadmium Telluride. *Nature Struct. Biol.* 1999, 6, 454–457.

21. Sodergren, S.; Hagfeldt, A.; Olson, J.; Lindquist, S. E. Theoretical Models for the Action Spectrum and the Current-Voltage Characteristics of Microporous Semiconductor Films in Photoelectrochemical Cells. *J. Phys. Chem.* 1994, 98, 5552.

22. Papageorgiou, N.; Graetzel, M.; Infelta, P. On the Relance of Mass Transport in Thin Layer Nanocrystalline Photoelectrochemical Solar Cells. *Sol. Energy Mater. Sol. Cells* 1996, 44, 119.

23. Mathew, D.; Infelta, P.; Graetzel, M. Dye-Sensitized Solar Cell. *Sol. Energy Mater. Sol. Cells* 1996, 53, 29.

24. Ferber, J.; Stangl, R.; Luther, J. An Electrical Model of the Dye-Sensitized Solar Cell. *Sol. Energy Mater. Sol. Cells* 1998, 53, 29–54.

25. Bisquert, J.; Vikhrenko, V. S. Interpretation of the Time Constants Measured by Kinetic Techniques in Nanostructured Semiconductor Electrodes and Dye-Sensitized Solar Cells. *J. Phys. Chem. B* 2004, 108, 2313–2322.

26. Gagliardi, A.; der Maur, M. A.; Gentilini, D.; Di Carlo, A. Modelling of Dye-Sensitized Solar Cells Using a Finite Element Method. *J. Comput. Electron.* 2009, 8, 398–409.

27. Gagliardi, A.; Mastroianni, S.; Gentilini, D.; Giordano, F.; Reale, A.; Brown, T. M.; Carlo, A. D. Multiscale Modeling of Dye Solar Cells and Comparison with Experimental Data: Selected Topics in Quantum Electronics. *IEEE J.* 2010, 16, 1611–1618.

28. Miettunen, K.; Halme, J.; Visuri, A. M.; Lund, P. Two-Dimensional Time-Dependent Numerical Modeling of Edge Effects in Dye Solar Cells. *J. Phys. Chem.* C 2011, 115, 7019–7031.

29. Kline, S. J.; McClintock, F. A. Describing Uncertainties in Single Sample Experiments. Mechanical Engineering, January 1953.