

IMPACT OF TEMPERATURE, IRRADIATION DURATION ON PERFORMANCE OF ORGANIC/RU-DYE/INORGANIC SOLAR CELLS

 **Hmoud Al-Dmour**

Mutah University, Faculty of Science, Department of Physics., 61710, Jordan

Corresponding Author e-mail: hmoud79@mutah.edu.jo

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This study investigates the impact of ambient conditions on the performance of P3HT/Ru-dye/nc-TiO₂ solar cells (TLSCs). It has been found that the increase of temperature and irradiation duration affect on the parameters of TLSCs. When the temperature was increased from 293 K to 393 K, the short circuit current density (J_{sc}) and open circuit voltage (V_{oc}) decrease from 2.2 to 1.7 mA/cm² and 0.7 V to 0.5 V respectively. That is attributed to the effect of high temperature on recombination of photo-generated charges and reduction of shunt resistance (R_{sh}) in the TLSC. Moreover, we also present the effect of irradiation duration on performance of the TLSCs. The measurement reveals that J_{sc} decreased by 0.5 mA/cm² while V_{oc} decreased by ~ 0.18 V during 4800 s illumination. This decrease suggests the filling of traps or defects at the interface with photo-generated charges. Finally, the maximum output power of TLSCs dropped by almost half within 6 days during a 20-day test because of affecting atmosphere moisture on the interface properties between dye/nc-TiO₂ and P3HT.

Keywords: *Solar cells; Temperature; Defects; Illumination; Oxide Surface; Efficiency*

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1. INTRODUCTION

Dye-sensitized solar cells (DSSCs), also known as Graetzel cells, have received significant attention for high power conversion efficiency and low cost in comparison with silicon solar cells [1, 2, 3]. The DSSCs are composed of a hole-transporting material (HTM) and a layer of nanocrystalline titanium dioxide (nc-TiO₂) coated with ruthenium-based sensitizers [4]. When light falls down on the DSSCs, it is absorbed by the sensitizer layer. That leads to generate an electron-hole pair (exciton) at the interface and contributes to the photo current of the cell. DSSCs have employed liquid electrolytes to transport holes to the top electrode and nc-TiO₂ to inject electrons into the bottom electrode [1]. However, the use of liquid electrolytes encounters various challenges, including evaporation and leakage, particularly during the sealing process of the cell [5]. Therefore, Different materials have been used to replace electrolyte in DSSCs [4,6,7]. For example, SAl-Taweel studied effect of thiophene rings rigidity on P3HT/dye/nc-TiO₂ solar cell performance [4]. On other hand, the effect of nanocrystalline TiO₂ (nc-TiO₂) morphology on the performance of polymer heterojunction solar cells was investigated. It was found that the parameters of the solar cell were influenced by the size and shape of the nc-TiO₂ particles, thereby affecting the power conversion efficiency [6]. Another investigation focused on the role of a compact TiO₂ layer between the bottom electrode and the nonporous TiO₂ layer in dye-sensitized solar cells [8]. The findings indicated that this layer improved the photovoltaic performance of the cells. A lot of experimental and theoretical works have been conducted to understand how the ambient conditions may influence the performance and durability of solar cell [9,10]. The ambient conditions include temperature, radiation exposure and lifetime of solar cells which influence on their charge carrier mobility, rate of charges recombination and overall device stability, thereby affecting the photovoltaic performance of such solar cells. In this study, we investigate the effect of ambient conditions on the parameters of P3HT/Ru-dye/nc-TiO₂ solar cells especially the open circuit voltage and short circuit current density. These measurements are vital for optimizing the design and operation of solar energy systems composed of polymer, Ru-dye, and nanocrystalline titanium dioxide materials.

2. EXPERIMENTAL PART

In this work, the solar cells are fabricated on fluorine-doped tin oxide (SnO₂:F) substrate, which are pre-coated with a thin, dense layer of titanium dioxide (TiO₂) working as bottom electrode. This substrate was purified by rinsing with ethanol and drying to remove adsorbed moisture. nc-TiO₂ paste was spread onto the substrates using a doctor blade and thin adhesive tape as a spacer. After removing the tape, the substrates were heated gradually up to 450°C and held at that temperature before cooling to room temperature. The sensitization process involved immersion of the sintered film in a solution of ruthenium 535 in ethanol, followed by rinsing and drying. A solution of P3HT in chloroform was prepared and placed onto the surface of nc-TiO₂, followed by spinning. The top electrodes were made of gold electrode and evaporated onto the P3HT layer through a shadow mask with circular holes [4].

Current-voltage (I-V) characteristics were obtained using a Keithley model 4200 source-measure unit. Illumination was provided by a solar simulator with incident power of 100 mW/cm², constrained by an aperture to fall on the device area. The temperature of the solar cells could be varied from room temperature to 120°C by means of resistance heater

mounted in the back of the copper stage. Temperature control was achieved using a Eurotherm 91 temperature controller connected to a power supply. Figure 1 shows the system in which the solar cells were mounted on a copper stage. Measurements were done in air. For electrical measurements, contact was made to the solar cells using fine gold wire and silver paste. The gold wire was connected to sockets in the lid of the chamber.

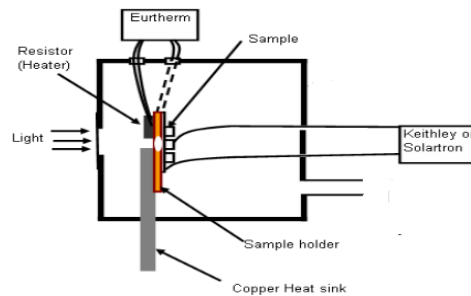


Figure 1. The system and sample holder are used in this work

3. RESULTS

Figure 2a,b show the J-V characteristic of the P3HT/Ru-dye/nc-TiO₂ solar cells (TLSC) in linear and semi logarithmic forms respectively. The device exhibits typical characteristics of a photovoltaic device. Under forward bias conditions (0 V to 1 V) in the dark, the device starts to conduct strongly at a turn-on voltage ~0.65V with rectification ratio estimated to be 3000 at +1 and -1v. Under solar simulation (100 mW/cm²), the device produced an open circuit voltage, V_{oc} ~0.73V a short circuit current density, J_{sc} ~2.3mA/cm² and a fill factor, FF, 49%. The power conversion efficiency was 1.1% and so lower than observed with nc-TiO₂ /electrolyte solar cells [1]. On other hand, TLSC Produced high short circuit density than double layer solar cells published in our previous work [6]. It was an order of magnitudes greater in the TLSCs.

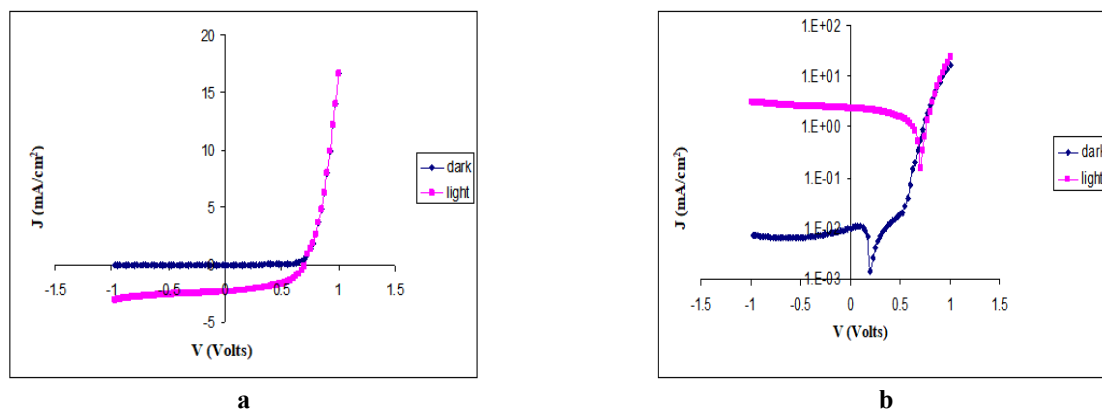


Figure 2. J-V characteristics of a TLSC
 a) In linear form, b) in semi logarithm form

In the dark, the J-V characteristics show that our solar cells behave as an ideal diode with good rectification. Under forward bias conditions, holes are injected into the highest occupied molecular orbital (HOMO) of P3HT from the gold electrode. Also, electrons are injected from the bottom electrode into the conduction band (CB) of nc-TiO₂ film. Thus, the forward current would be expected to be high because the injection of charge carriers from the electrodes to P3HT is energetically favored. Under reverse bias, electron injection from the gold electrode to the LUMO (lowest occupied molecular orbital) of P3HT and holes from SnO₂:F to the conduction band of nc-TiO₂ are not favored. This interpretation only applies because we assume no band bending at the P3HT/nc-TiO₂ interface because it is suppressed by the intermediate Ru-dye layer. The dark current passing through the P3HT/Ru-dye/nc-TiO₂ interface is dominated by transport across this interface. Under light conditions, the photo-generation process relies on photon absorption by both the dye and P3HT. The excitons generated close to the interface dissociate. Electrons from the P3HT and/or dye will transfer to the conduction band of the nc-TiO₂. Holes generated in the P3HT together with those released into P3HT in order to regenerate the dye are transported to the gold electrode [11]. Like all other solar cells, the parameters of TLSC solar cells are sensitive to the ambient conditions [12, 13]. Figure 3 shows that the current-voltage characteristics of device a function of temperature. As seen, both J_{sc} and V_{oc} decrease with increasing temperature (see Figure 4a and b). The open circuit voltage remains relatively constant at around 0.7V until the temperature reaches approximately 330K. After this point, V_{oc} decreases to around 0.43V at 397K. In addition, the slope of the I-V curve in the third quadrant also decreases which can be attributed to a decrease in the shunt resistance R_{sh}. Furthermore, in the first quadrant of the I-V plot, there was an initial small increase in the slope of the curve as the temperature increased but it then decreased as the temperature continued to increase.

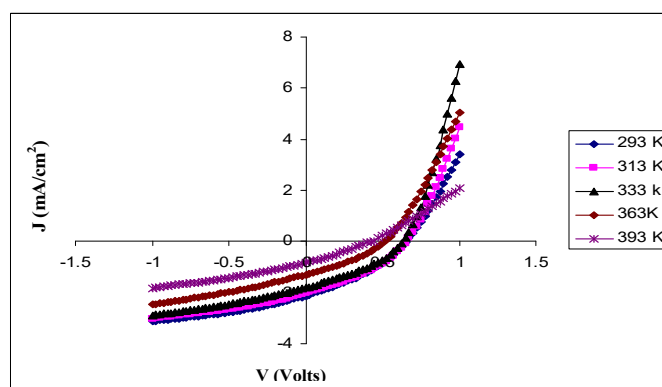


Figure 3. J-V characteristics of TLSCs plotted as function of temperature

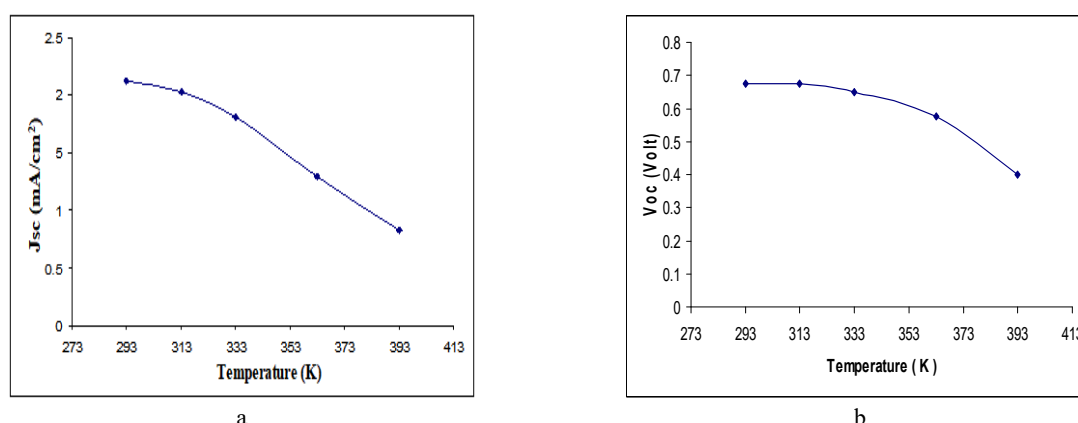


Figure 4. The variation of Jsc (a) and Voc (b) with temperature for a TLSC

In real devices, both series resistance (R_s) and shunt resistance (R_{sh}) of solar cells have values determined by the electrical properties of the materials forming the devices as well as by the nature of the interfaces [14,15]. R_{sh} must be as large as possible so as to minimize the loss of current internally while R_s needs to be as small as possible to reduce the loss of voltage internally. When the effect of R_s and R_{sh} are taken in account, the relation between output current, I_{out} , and output voltage, V_{out} is equal to

$$V = V_{out} + I_{out}R_s \quad (1)$$

Under this condition, the open circuit voltage (V_{oc}) is obtained when $I_{out} = 0$, and described by

$$V_{oc} = \frac{kT}{q} \ln \left(\frac{I_g}{I_o} + 1 - \frac{V_{oc}}{I_o R_{sh}} \right) \quad (2)$$

From equation 2, V_{oc} is affected by the photogenerated charges (denoted by I_g) and the recombination of photogenerated charges (denoted by R_{sh}). Therefore, increasing the temperature of solar cells enhance the mobility of charge carriers and carrier concentration which cause to reduces the series resistance in the bulk region. If this assumption is applied and recombination of charges was unchanged with temperature, V_{oc} should have increased with temperature to maintain open circuit condition i.e. $I_{out} = 0$. Therefore, we consider that the recombination of photogenerated charges must also increase with increase in temperature i.e. a reduction occurs in R_{sh} and V_{oc} as seen in figure 4-a The thermal activation energy of P3HT / Ru-dye / TiO_2 solar cells was calculated using equation 3 and figure 4-b

$$V_{oc} = \frac{KT}{q} \ln \left[\frac{J_p}{qSN_c} \right] + \frac{E_c - E_F}{q} \quad (3)$$

where S is the interface recombination velocity, N_c is the effective density of states in the conduction band of the TiO_2 .

Thermal energy refers to the energy needed for charge carriers to overcome energy barriers within the device structure, including those at interfaces and within the bulk material. By extrapolating to $T = 0K$ (Figure 5), the thermal activation energy, E_a , of the TLSCs was estimated to be $\sim 1.3eV$. This value is expected to depend on the HOMO of P3HT and the conduction band of $nc-TiO_2$. However, the difference between the LUMO of P3HT and conduction band of $nc-TiO_2$ was 0.9 eV. The difference between the two values (1.3eV and .9eV) may be caused by the NCS group of the Ru dye absorbed on $nc-TiO_2$ surface. It will contribute around 0.4 eV in thermal activation energy by forming a surface dipole

on nc-TiO₂ [16]. Additionally, the Fermi level of P3HT is affected by temperature which may also lead to an increase in the thermal activation.

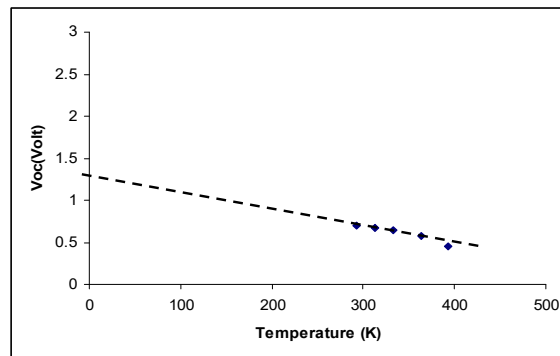


Figure 5. Voc versus temperature of TLSCs after extrapolation of Voc values
 The curve is intercepted Y axis at 1.3eV where the temperature is zero

On other hand, the increase in temperature also improves the conductivity of P3HT and reduce the series resistance. However, there was no indication of improvement in the value of Jsc when the temperature increases from 293 K to 313K. This is attributed to the strong effect of the temperature on Voc. Thus, the decrease in Jsc when the Voc decreased from 0.7 V to 0.45V caused a shift in the I-V curve as the temperature increased. Figure 6 shows the irradiation time dependence of the Jsc and Voc. The results reveals that there is an initial slight decline, both the short-circuit current density and open-circuit voltage remained relatively stable over a 4800-second period of irradiation. Throughout this duration, Jsc decreased by 0.5 mA/cm² under illumination, while Voc experienced a decrease of approximately 0.18 V.

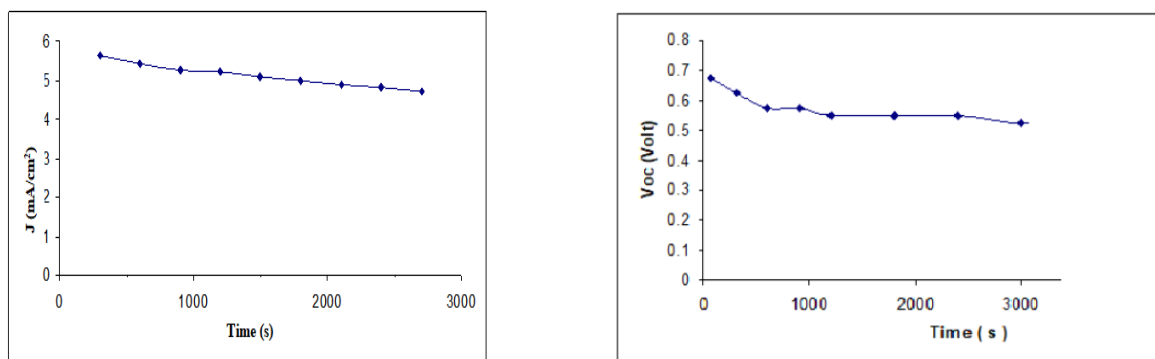


Figure 6. a) Jsc and b) Voc as function of photo irradiation time for TLSCs

The device demonstrates good stability, with the short-circuit current density (Jsc) slightly increasing during the first 10 days of testing, followed by a gradual decline over the next 20 days. Conversely, the open-circuit voltage (Voc) slowly decreases throughout the same period. Although noting the effect at time on Voc and Jsc are important for establishing the operating limits of the device, the greater significance is the output power. This is shown in Figure 7 where the output power is plotted as a function of the forward voltage applied to the device. Over the first 6 days, the output power increased slightly to 0.8mW/cm² reflecting the increase in Jsc. The maximum output power then decreased reaching 0.45mW/cm after 20 days.

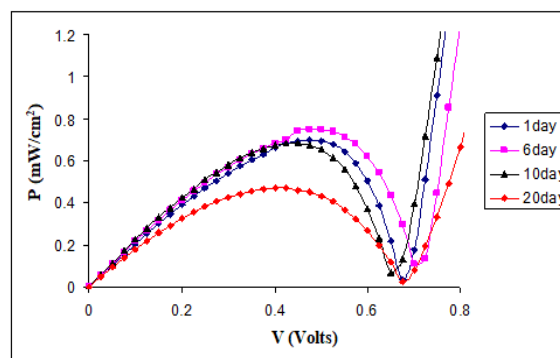


Figure 7. The output power versus voltage of age time for TLSC

The J_{sc} of TLSCs increased in the first few seconds of irradiation then it started to decrease slowly over a few thousand seconds. This is due to filling of traps or defects at the interface produced by absorbed oxygen and water vapor on the nc-TiO₂ surface [17]. This leads to an increase in the J_{sc} in the first few seconds. However, these defects were unlimited and regenerated from absorbing oxygen, so that, the J_{sc} decreased after the first seconds of illumination. The V_{oc} of the TLSCs decreased in the first few seconds also as a result of traps filling (defects) at the interface. When TLSCs were tested over a period of 20 days, the change in J_{sc} and V_{oc} were relatively small. However, the maximum output power decreased to almost half the maximum observed value observed after 6 days. Although the TLSC were stored in the dark between measurements, they were, nevertheless, exposed to the atmosphere. We assume therefore that the degradation in performance was due to the oxygen and/or atmosphere moisture affecting at the interface properties between dye/ nc-TiO₂ and P3HT.

4. CONCLUSION

This study examines the impact of ambient conditions on solar cell performance. Results demonstrate a clear relationship between temperature, irradiation duration, and stability with open circuit voltage (V_{oc}) and short circuit current density (J_{sc}). Increasing temperature leads to a decrease in both J_{sc} and V_{oc} because of photogenerated charges and the recombination of photogenerated charges. Irradiation duration also impact the performance, with J_{sc} and V_{oc} decreasing over time, due to trapping effects at the interface. While solar cells exhibit stable J_{sc} and V_{oc} over a 20-day test period, their maximum output power decreases significantly within 6 days.

ORCID

©Hmoud Al-Dmour, <https://orcid.org/0000-0001-5680-5703>

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ВПЛИВ ТЕМПЕРАТУРИ, ТРИВАЛОСТІ ОПРОМІНЮВАННЯ НА РОБОТУ ОРГАНІЧНИХ/RU-DYE/НЕОРГАНІЧНИХ СОНЯЧНИХ ЕЛЕМЕНТІВ

Хмуд Аль-Дмур

Університет Мута, факультет природничих наук, кафедра фізики, 61710, Йорданія

У цьому дослідженні вивчається вплив навколишніх умов на продуктивність сонячних елементів P3HT/Ru-dye/nc-TiO₂ (TLSC). Встановлено, що підвищення температури та тривалості опромінення впливає на параметри TLSC. При підвищенні температури з 293 К до 393 К густина струму короткого замикання (J_{sc}) і напруга холостого ходу (V_{oc}) зменшуються з 2,2 до 1,7 мА/см² і від 0,7 В до 0,5 В відповідно. Це пояснюється впливом високої температури на рекомбінацію фотогенерованих зарядів і зменшення опору шунта (R_{sh}) у TLSC. Крім того, ми також представляємо вплив тривалості опромінення на продуктивність TLSC. Вимірювання показує, що J_{sc} зменшився на 0,5 мА/см², тоді як V_{oc} зменшився на ~ 0,18 В протягом 4800 с освітлення. Це зменшення свідчить про заповнення пасток або дефектів на межі розділу фотогенерованими зарядами. Нарешті, максимальна вихідна потужність TLSC впала майже вдвічі протягом 6 днів під час 20-денного випробування через вплив вологості атмосфери на властивості розділу між барвником/nc-TiO₂ і P3HT.

Ключові слова: сонячні елементи; температура; дефекти; освітлення; поверхня оксиду; ефективність