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Titanium Dioxide (TiO2) and Gel-Polymer Solar Cells: Structures and Performance Evaluation

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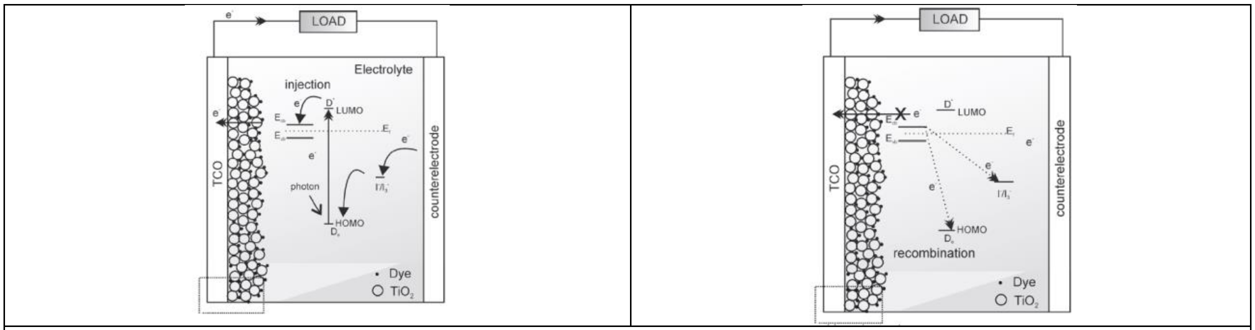
Abstract---*This research focuses on the study of semiconductor-based solar cells utilizing titanium dioxide (TiO2) and gel-polymer electrolytes. The technology for preparing the electrolytes used in these solar cells has been developed, encompassing both liquid and gel polymer electrolyte compositions. The electrochemical impedance method is employed to determine important parameters such as diffusion coefficient, mobility, and charge carrier concentration in both liquid and gel-polymer electrolytes. Experimental results are compared with theoretical calculations utilizing the electrochemical impedance spectroscopy graph. Moreover, the photon-to-current conversion efficiency of the semiconductor-based solar cells is determined using the Incident Photon to Current Conversion Efficiency (IPCE) method, covering a wavelength range of 300 nm to 900 nm.*
Keywords---*gel-polymer solar cells, impedance spectroscopy, IPCE, semiconductor-based, Titanium Dioxide (TiO2)*

Introduction

New generation thin film solar cells (DSSC-Dye sensitized solar cell) different aspects from traditional semiconductor solar cells and the results of researching the structure, manufacturing technologies and photovoltaic characteristics of this type of solar cells were studied (Agarwala et al., 2011). An analysis of some physical parameters of the solar cell is presented along with the formation process of free charge carriers in semiconductor-based DSSCs and electrophysical parameters studied by world scientists (Aram et al., 2015). Based on these, the goals and objectives of the dissertation work are defined (Wang et al., 2018; Enea et al., 1989). KThe principle of operation of QEs with highly sensitive dyes consisting of multilayer structures is presented in Figure 1.



(a) (b)

Figure 1. Principle of operation of a) n-type and b) p-type semiconductor highly sensitive dye solar cells and their physical processes

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The graph of the results obtained by the method of electrochemical impedance spectroscopy of the electrolyte is shown in Fig. 2.

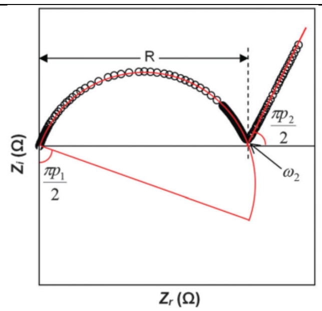

Figure 2. Graph of electrochemical impedance spectroscopy of electrolyte

Materials and Methods

It is known that the real and abstract parts of the electrolyte resistance impedance are expressed by the following formulas:

$$Z_r = \frac{\cos\left(\frac{\pi p}{2}\right)}{k^{-1}\omega^p} \tag{1}$$

And

$$Z_i = \frac{sin\left(\frac{\pi p}{2}\right)}{k^{-1}\omega^p} \tag{2}$$

Here Z_r and Z_i are the real and abstract parts of the impedance, respectively, ω is the frequency, p in these expressions is determined from Figure 2, that is, $p = \frac{2tg\alpha}{\pi}$. The real part of the impedance is equal to the active resistance, i.e., this $Z_r = R$ quantity is determined using the electrochemical impedance spectroscopy graph of the electrolyte. k is the inverse quantity of the electric capacity of the electrolyte, it is

$$C = k^{-1} = \frac{\varepsilon_r \varepsilon_0 S}{d} \tag{3}$$

determined from the formula. In this formula, ε_r is the relative dielectric constant of the electrolyte, ε_0 is the electric constant, S is the surface of the electrolyte and contact boundaries, d is the thickness of the electrolyte layer (Krishna et al., 2022; Beadling et al., 2013). The ion conductivity of the sample σ was calculated using the following formula:

$$\sigma = \frac{l}{RS} \tag{4}$$

where l is the thickness of the electrolyte, R is the active resistance of the electrolyte, S is the surface of the electrolyte.

The diffusion coefficient D, mobility μ, and concentration n of free ions in the electrolyte are determined using the following formulas:

$$D = \frac{d^2}{\tau} \tag{5}$$

Here - is the frequency that corresponds to the smallest value of u. (3) from formula $\tau = \frac{1}{\omega};\ \omega Z_i$

here $\tau = \frac{1}{\omega};\ \omega$ is the frequency corresponding to the smallest value of Z_i.

$$d = k\varepsilon_r\varepsilon_0 S \tag{6}$$

knowing that, using (5) and (6), we can derive the expression for the diffusion coefficient:

$$D = \frac{(k\varepsilon_r\varepsilon_0 S)^2}{\tau} \tag{7}$$

mobility of charge carriers μ is expressed by the Nernst-Einstein formula as follows:

$$\mu = \frac{eD}{k_b T} \tag{8}$$

where k_b - Boltzmann's constant, T - absolute temperature, e - electron charge.

From expressions (7) and (8), we can derive the following to calculate the mobility of charge carriers:

$$\mu = \frac{e(k\varepsilon_r\varepsilon_0 S)^2}{k_b T\tau} \tag{9}$$

ionic conductivity of the electrolyte

$$\sigma = n\mu e \tag{10}$$

determined using the formula. The concentration of charge carriers n can be expressed using formulas (9) and (10) above as follows:

$$n = \frac{\sigma k_b T\tau}{(ek\varepsilon_r\varepsilon_0 S)^2} \tag{11}$$

Using the above expressions (7), (9) and (11), the diffusion coefficient, mobility, and concentration of charge carriers of the electrolyte are determined (Azeez & Fedkiw, 2010; Huo et al., 2008). It is known that V_{oc} -salt operating voltage (Open circuit voltage), J_{sc} -short circuit current density (short circuit current), maximum current (I_{max}), maximum voltage (V_{max}), filling factor (FF) and efficiency of solar cells are useful duty factor (η) is the main photoelectric parameter. The fill factor of semiconductor-based DSSCs was expressed by the following formula:

$$FF = \frac{J_{max} * V_{max}}{J_{sc} * V_{oc}} \tag{12}$$

Where J_{max} and V_{max} are the maximum current density and maximum voltage, respectively, J_{sc} is the short-circuit current density, and V_{oc} is the normal operating voltage (Zhang & Rhim, 2022; Fujishima et al., 2000). The energy efficiency of DSSC, that is, the useful work coefficient, can be expressed as follows:

$$\eta(\%) = \frac{V_{oc} \times J_{sc} \times FF}{P_{in}} \times 100\% \tag{13}$$

where P_{in} is the intensity of light falling on the working surface of the solar cell.

Semiconductor based DSSC in solar elements the modulated photocurrent intensity spectroscopy (IMPS) and modulated photovoltage intensity spectroscopy (IMVS) methods were used to determine the electron transport time and mean residence time (Boukamp, 2004; Ates, 2011). The IMPS experiment allows us to determine the electron transport time, which is defined as:

$$\tau_{tr} = \frac{1}{2\pi f_{IMPS}} \tag{14}$$

Here f_{IMPS} is the maximum frequency of IMPS for DSSC.f_{IMPS}
In addition, the average residence time of an electron was determined using the IMVS experiment.

$$\tau_{\mathrm{rec}} = \frac{1}{2\pi f_{\mathrm{IMVS}}} \qquad (15)$$

wheref_{IMVS} is the maximum frequency of IMVS for DSSC. IMPS and IMVS graphs obtained as a result of the experiments are shown in Figure. 3.

Knowing the electron transport time and residence time, other important parameters for solar cells - charge collection efficiency (η_{coll}), electron diffusion coefficient (D) and electron free running distance *(L_n)* can be determined using the following formulas:

$$\eta_{coll} = 1 - \frac{\tau_{tr}}{\tau_{rec}} \qquad (16)$$

$$D = \frac{d^2}{2.35\tau_{tr}} \qquad (17)$$

$$L_n = \sqrt{D\tau_{rec}} \qquad (18)$$

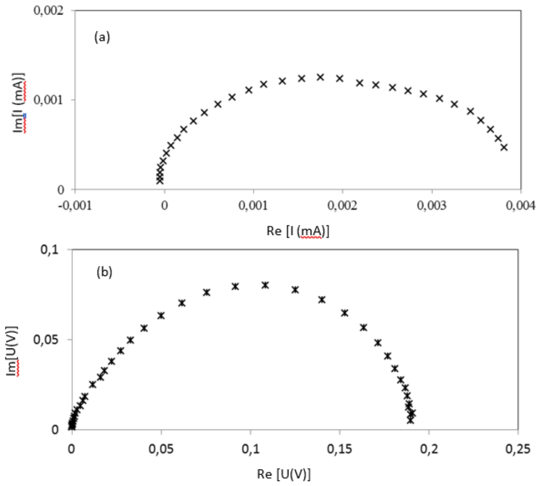

Figure 3. View of a) IMPS and b) IMVS graphs

Results and Discussion

Semiconductor based DSSCin solar elementsphoton to current conversion efficiency was determined by the IPCE method (Incident photon to current conversion efficiency) in the wavelength range from 300 nm to 900 nm (Bandara et al., 2019; Careem et al., 2017). The graph of IPCE is presented in Figure 4.

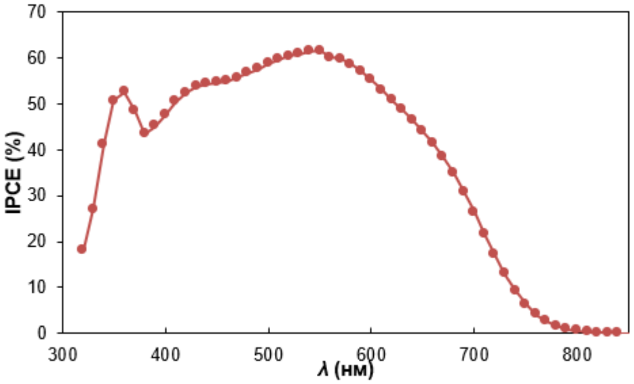

Figure 4. Photocurrent conversion efficiency (IPCE) graph of photons incident on a solar cell composed of TiO_2-based dyed multilayer structures with semiconductor properties

Conclusion

From the experiment, it was found that the parameters of the liquid electrolyte presented in the table are greater than those of the gel polymer electrolyte. It was shown above that the value of these parameters depends on the mobility, concentration and diffusion coefficient of charge carriers in the electrolyte. Semiconductor DSSC based on liquid and gel polymer electrolyte the it was found that increasing the amount of TPAI in the electrolyte from 0.05 g to 0.25 g increases the efficiency of solar cells. Based on the experiments, the photoelectric characteristics of semiconductor DSSCs were determined and the obtained results are presented in Tables 4-5. The experimental results showed that the parameters of the electrolyte-based solar cell with a mass of 0.25 g of TPAI will be significantly larger. It was found that with the increase of TPAI content in the electrolyte from 0.05 g to 0.25 g, the working efficiency of DSSC based on liquid electrolyte doubled, from 3.29 to 6.74%.

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