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Short Communication

Design of a Semiconductor Photoelectrochemical Cells Using Orange Dye and NaCl Aqueous Solutions

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This paper describes a new design of the semitransparent photo-electrochemical cells using the orange dye ($C_{17}H_{17}N_5O_2$) and NaCl aqueous solutions. In the proposed design, the semi-transparency is realized by fabrication of the light receiving surface using a series of transparent and opaque strips. This new design facilitates the easier fabrication of the semitransparent electrochemical devices. The photo-electrochemical cell showed promising results to be potentially used for the low power energy generation and photo-sensing applications.

Keywords: Semi-transparent, photo-electrochemical, energy harvesting, orange-dye, p-Si, open circuit voltage, short circuit current

1. INTRODUCTION

Conventional photoelectrochemical cells are comprises of photoactive semiconducting active electrode and a metallic or semiconductor counter electrode [1]. Both the anode and cathode are dipped in the electrolyte solution comprising appropriate redox couples [2]. If we evaluate metal/electrolyte and semiconductor/electrolyte interfaces, in the case of semiconductor/electrolyte junction the voltage drop happens on the both semiconductor as well as solution sites. However, in the case of metal/electrolyte junction the voltage drop appears completely at the electrolyte site. Therefore, the charge distribution takes place deeper in the inner of the semiconductor, generating a space-charge-region.

Different types of semiconducting p/type and n/type substrates such as Si, GaAs, GaP, $GaInP_2$, $CuFeO_2$, are extensively studied as electrodes material [3]. Porous-Si layer photoelectrodes exhibits stable photodiode characteristics because of porous structure of the Si surface and very useful in suppressing the dark current of the photoelectrochemical cell [4]. Iron-oxide/*n*Si which works as hetero-junction electrode has also been reported. The photo-current at such hetero-junction photoanodes is produced by the holes those are photoexcited on both iron-oxide and *n*-Si surfaces [5]. Further alteration of electrode by a layer of evaporated Pd can greatly enhanced the photocurrent [6].

Orange dye (OD) is a p/type organic semi-conductor and has ultimate application ability in electrochemical cells. It has superb solubility in H_2O, decent photo-absorption in visible range, good conductivity in distilled water. These interesting feature makes it applicable in storage devices, energy conversion and sensors. A bilayer thermoelectric cell built on flexible ITO substrate using OD experiences 30 % higher thermoelectric voltages as compared to controlled ITO based cell [7]. An electrochemical cell prepared by Zn/orange dye aqueous solution/carbon cell with current discharge/charge efficiency to be 67% [8]. Furthermore, the effect of humidity on the functioning of organic bilayer OD/ITO thermoelectric cells (OD is orange dye) has also been investigated. The photo thermoelectric effect in Zn/OD in H_2O solution/carbon cell was studied in [9].

We aimed to design, fabrication and investigating the semitransparent photo-electrochemical cell using the aqueous solutions of orange dye and NaCl. This new design approach of the photo-electrochemical cell facilitates easier fabrication of the semitransparent electronic devices. In proposed design, the semi-transparency is realized by the fabrication of the light receiving surface using a series of transparent and opaque strips.

2. EXPERIMENTAL

This section describes fabrication of the semitransparent photo electrochemical cell based on p-type Si and orange dye (as semitransparent electrolyte). A modified version of OD has been used as the electrolyte. The modified OC obtained by adding 2 wt.% of NaCl to the aqueous solution of the orange dye 3wt.%. The NaCl increases the ionic conductivity of the aqueous solution. Figure1 shows molecular structure and UV-visible absorption spectra of modified OD. The schematic illustration of the fabricated semitransparent electrochemical cells as shown in Figure 2. To fabricate the electrochemical device boron doped (doping concentration: 8×10^{15} cm^{-3}) p-type mono-crystalline (crystal orientation: <100>) Si was used. The resistivity and thickness of the Si wafer was 180 µm and 1.8 ohm/cm, respectively. The Silicon wafer was textured from both sides (random pyramid). The actual sizes of the electrochemical cells were $3 \times 3 \times 1.5$ cm^3. The area of the p-Si strips was 2.5×0.3 cm^2, while the size of the ITO electrode was 2.5×2.5 cm^2. For the I-V measurement, digital meters DT 4253 was used. As a visible light source, the filament lamp was used, and the light intensity was measured using lux-meter (LM-80 AMPROBE). The HP3616 (Philips) has been used as a source of infrared irradiation whereas the intensity of the infrared irradiation was measured using the IR power meter LS122.

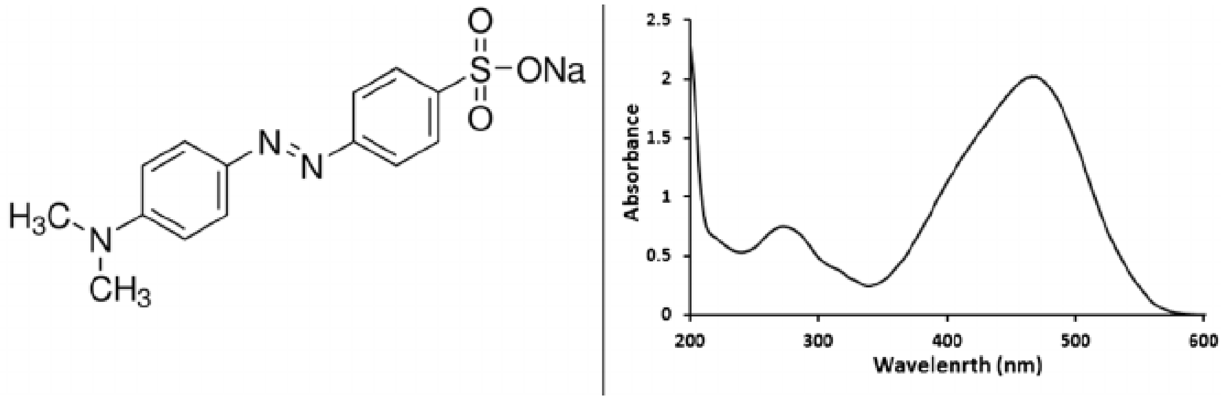

Figure 1. Molecular structure and UV-visible absorption spectra of modified orange dye ($C_{17}H_{17}N_5O_2$).

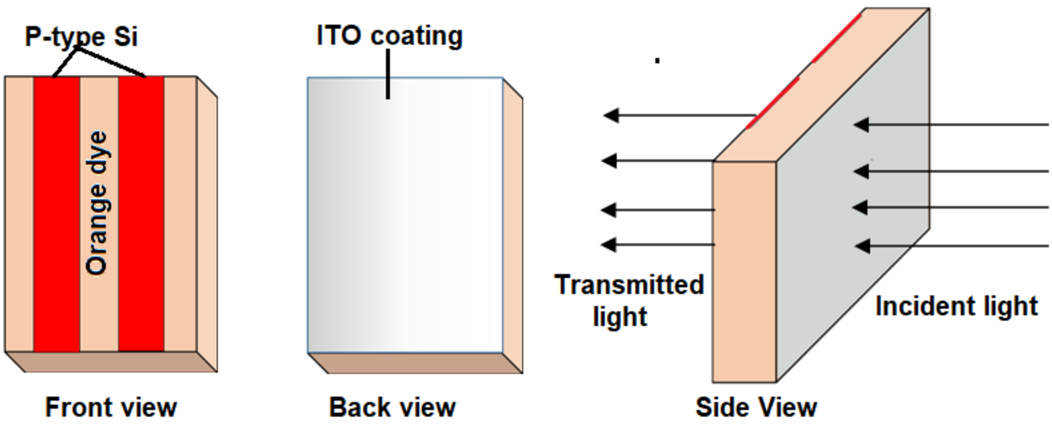

Figure 2. Schematic diagram of the semitransparent p-Si-OD-NaCl-ITO electrochemical cell.

3. RESULTS AND DISCUSSION

Figure 3 shows a quasi-linear correlation between open circuit voltage (V_{oc}) and intensity of infrared irradiation (IR) for the semitransparent p-Si-OD-NaCl-ITO electrochemical cells. When the electrochemical cells are illuminated using IR radiation, initial voltage produced is 73mV at 0 W/m^2, with increase of IR intensity voltage increases to 150 mV at 700 W/m^2. In absence of IR light, the polarity developed is due to the diffused light and the polarity was as follows: p-type Si → negative (-) and ITO→ positive (+). This behavior of the p-Si-OD-NaCl-ITO electrochemical cell may be due to the generation of the electron-hole pairs in p-type Si electrode and separation of the opposite charges by the electric field that is present due to the presence of the initial voltage 73mV. The relationship between short-circuit current and intensity of infrared irradiation for the semitransparent p-Si-OD-NaCl-ITO electrochemical cell is measured and is shown in Figure 3 (b). Initial current produced by the electrochemical cell in absence of IR radiation is 0.19 mA. This increased of IR illumination intensity to 700 W/m^2 the value increased to 0.42 mA. The relationship between short-circuit current and intensity of infrared irradiation is also observed to be nonlinear.

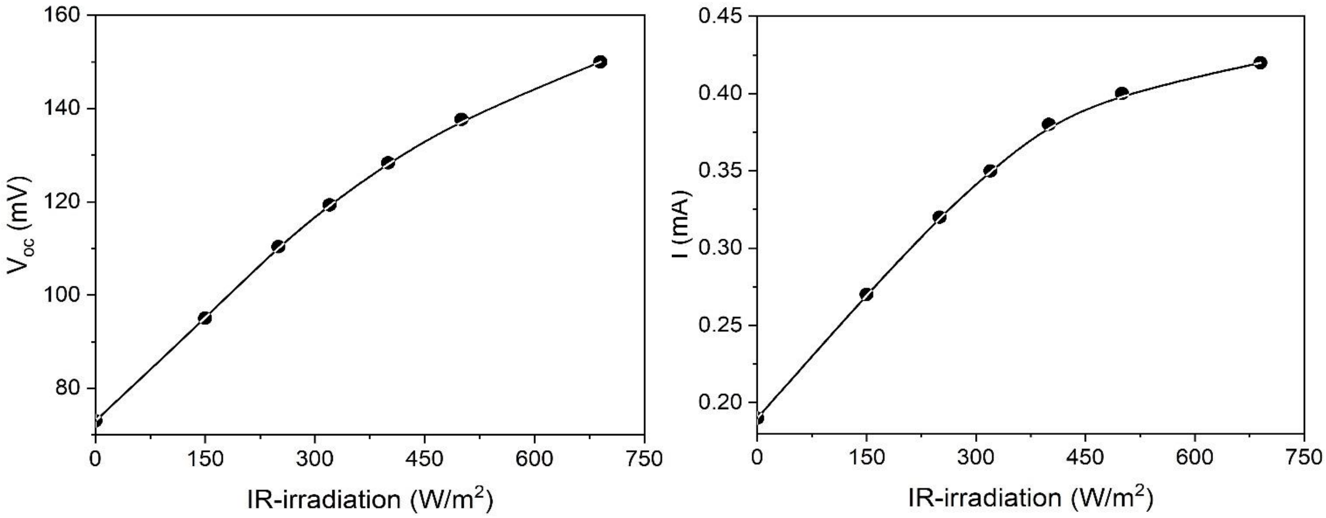

Figure 3. (a) Open-circuit voltage and intensity of infrared irradiation relationship for the semitransparent p-Si-OD-NaCl-ITO electrochemical cell. (b) Short-circuit current and intensity of infrared irradiation relationship for the semitransparent p-Si-OD-NaCl-ITO electrochemical cell.

Figure 4 show open-circuit voltage and short-circuit current relationships as a function of visible light illumination. It is observed that, the behavior is similar to characteristics observed for IR radiation. Experimental results shown in Figure 3(a) and Figure 4(a) can be described by the following expression:

$$y= ax^n + b \qquad (1)$$

In Eq. (1), ***y*** is the total voltage, ***b*** represents an initial output voltage of the semitransparent electrochemical cell under dark condition, ***x*** is the intensity of irradiation (IR/visible), ***n*** is the nonlinearity factor. In our case $1 \geq n \geq 0.5$, ***a*** is a coefficient which represent initial slope of the curves. The initial output voltages (***b***) are measured in Figure 3(a) and Figure 4(a). Replacement of the ITO by some other conducting material with different work functions may result in reversing the polarity of the voltage under dark condition. In this case, the photo-electrochemical cell would be "self-rechargeable". The investigation of this option will be the taken as a future assignment.

The observed results can be explained by traditional mechanism used to explain the effect of light into silicon crystals. When light photon incident on the semiconducting surface of the electrochemical cell two changes takes place. First the electron-hole pairs are generated and second the electric field which usually available in the silicon-OD solution interface separate electrons and holes. This electric field leads to development of the photo-induced voltage. At the same time the electrochemical effect observed under dark conditions is due to different electrochemical potentials of the silicon and ITO electrodes placed in the electrolyte containing OD and NaCl aqueous solution. The advantages of electrolyte comprising of OD and aqueous NaCl is that, firstly, it increases the conductivity of the aqueous solution. All the properties of the electrochemical cell are investigated for a period of two weeks and the cell is found to stable with no noticeable changes in the parameters.
Usually, photovoltaic devices demonstrate elevated PECs while they are illumined from the both sides. Similar effect is observed in the case of semitransparent p-Si-OD-NaCl-ITO electrochemical cell.

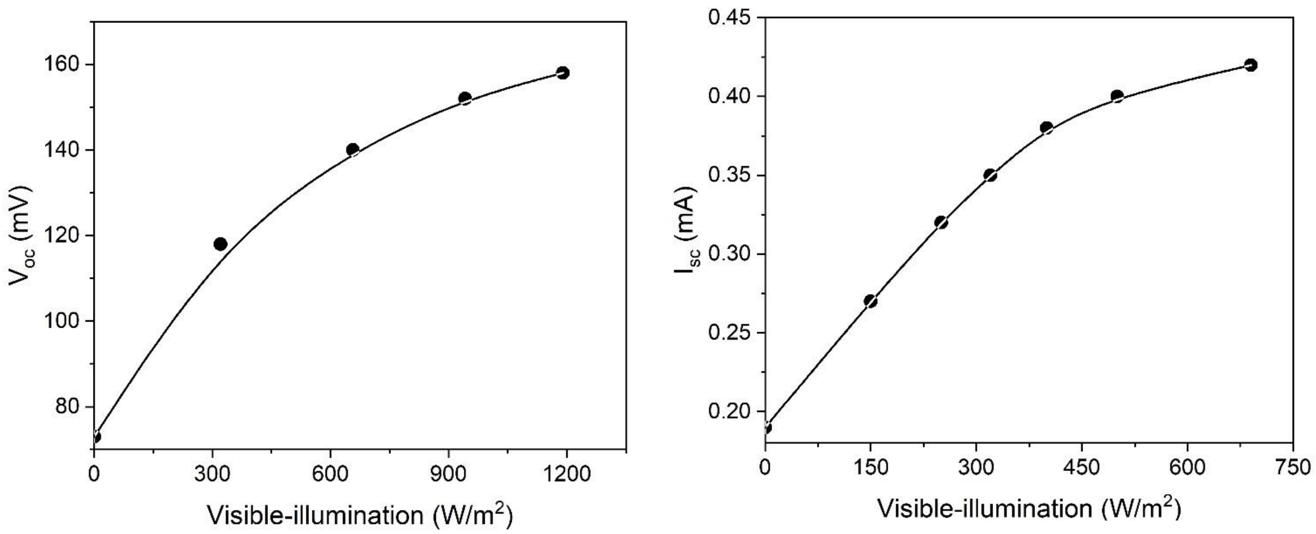

Figure 4. (a) Open-circuit voltage and intensity of visible light illumination relationship for the semitransparent p-Si-OD-NaCl-ITO electrochemical cell. (b) Short-circuit current and intensity of visible light illumination relationship for the semitransparent p-Si-OD-NaCl-ITO electrochemical cell.

The voltage-current characteristics of the semitransparent p-Si-OD-NaCl-ITO electrochemical cell shown at illumination of 1000 W/m^2 (Figure 5). These characteristics are similar to I-V characteristics of the electrochemical cells or organic semiconductor solar cells [2, 10, 11] Comparison of Figure 3(a) and Figure 3(b) shows that in both cases the open-circuit voltage and short-circuit current almost doubled when ordinary light is replaced by IR light at 700 W/m^2. The non-linearity of the short-circuit current and intensity of infrared irradiation relationship may be due to the possible change in the thickness of the depletion region across the surface of the p-type Si electrode which is in contact with the aqueous electrolyte. On the contrary, it is obvious that the ITO-electrolyte contact is not sensitive to the effect of the light. The properties of the cells were investigated over the period of two weeks and no noticeable changes in the electrochemical parameters of the cells were observed.

Recently, similar photoelectrochemical sensors were fabricated using Bi_4NbO_8Cl [12], nitrogen doped carbon/ZnO nanopolyhedra derived from ZIF-8 [13] and enzymatic oxydate [14]. Previously, the semitransparent perovskite-based photocells were made by coating graphene transparent electrodes on the top of the cell [15]. The cell performance was enhanced by increasing the conductivity of the graphene and the connection between the graphene and perovskite active layers in the coating process. The cells showed the improved performance when they were illuminated from the both sides. The same effect was observed in the case of semitransparent p-Si-OD-NaCl-ITO electrochemical cell fabricated by us.

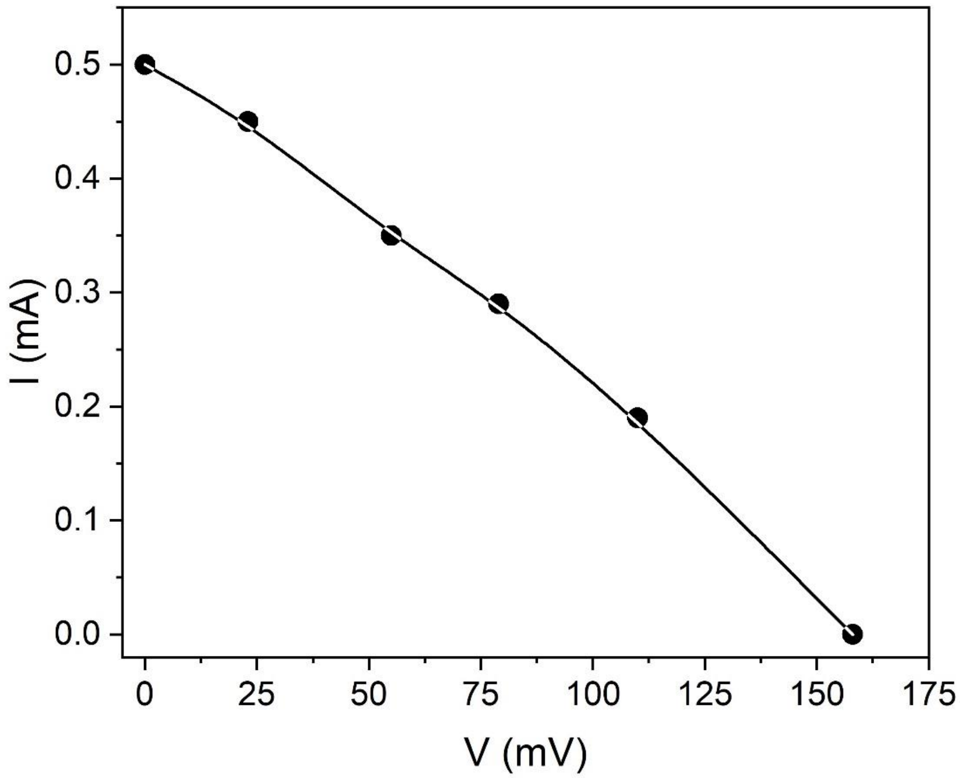

Figure 5. Volt-ampere characteristics of the semitransparent p-Si-OD-NaCl-ITO electrochemical cell at illumination of 1000 W/m^2.

4. CONCLUSION

In this paper the design, construction and investigation of the properties of semitransparent photo-electrochemical cells using p-Si and aqueous solution of orange dye and NaCl were described. The cells showed initial open-circuit voltage and short-circuit current under dark conditions. The open-circuit voltages short-circuit currents and current-voltage characteristics of the cells increased in a quasi-linear fashion when the cells were exposed to supplementary visible light and infrared sources. These aqueous solutions based electrochemical devices can be potentially used for the photo-electrochemical sensors.

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