Development and Empirical Investigation of a Self-Powered UV Detector Based-Microcontroller

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Abstract

Titanium dioxide Nano particles have been used as a core material for the design of low-cost sustainable power source, the dye sensitized cell. In this work, dye sensitized cell was investigated to be used as a self-powered ultra violet light detector in a data acquisition system. To enhance the detector robustness, the device was sealed using cross-linked photo resist to isolate it from the environmental effects. The detector was tested in air as well as in water to proof its characteristics in various environmental conditions. High responsivity and fast response were achieved for both discrete and continuous ultraviolet (UV) illuminations. To prove the self-powered property of the sensor, it was interfaced to a microcontroller. Our experimental results confirmed that there is no need of intermediate electronics such as signal conditioning in the interfacing circuit. Furthermore, the detector observed obvious selectivity for different light colors. This characteristic makes it candidate for the development of color sensors.

Keywords: Electronics, Self-powered, UV Detector.

الخلاصة

شهدت المجسات الاكترونية المصنوعة من مادة ثاني اوكسيد التيتانيوم اهتماما كبيرا نظرا لخواصها الالكترونية الملفته للانتباه وتطبيقاتها المتعددة وخاصة في مجال توليد الطاقة المستدامة الرخيصة الثمن. في هذا البحث استخدمت مادة الخلايا الصبغية الحساسة، المتضمنة في تركيبها مادة التيتانيوم في تصنيع مجس لتحسس الاشعة فوق البنفسجية بعد اجراء عدد من التعديلات على طريقة تصنيعه. لتحسين استقرارية المجس وعزله عن تاثيرات المحيط الخارجي تم تغليفه بمادة بوليمرية باستخدام تقنيات التصنيع المايكروي. تم دراسة المجس لمعرفة خواصه الالكترونية في محيط مفتوح وكذلك تحت الماء. اظهرت الاختبارات ان المجس ذو حساسية وسرعة استجابة عاليتين لكل من اشارات الاشعة فوق البنفسجية التماثلية منها والمتقطعة. ولاثبات خاصية القدرة الذاتية للمجس تم ربطه مع مسيطر مايكروي بدون استخدام مصدر قدرة لتغذية المجس وايضا بدون مكيف اشارة. كما واظهر المجس قابلية على تمييز الالوان مما يفتح الباب لاستخدامه كمجس لوني.

الكلمات المفتاحية: الإلكترونيك ، تغذية ذاتية، مجسات الأشعة فوق البنفسجية .

1. Introduction

To be able to use a UV sensor in the industrial or even in the military application, it must have physical and chemical features that promote sensitivity, selectivity, and robustness (Young *et.al.*, 2007b ; Chang *et.al.*, 2007; Averine and Kuznetzov, 2008; Wang *et.al.*, 2004; Bie *et.al.*, 2011; Young *et.al.*, 2007a ; Averine *et.al.*, 2008). The demands for accurate and fast UV sensors that will be able to provide precise measurement in the industrial process and environmental measurement have accelerated the development of new sensors technology. Several UV detectors technologies are currently available such as Si-based detectors and photomultipliers. In spite of the high sensitivity and fast response of those detectors, they have some property limits such as the need of filters and low efficiency specifically for the Si-based detectors (Munoz *et.al.*, 2001; Yang *et.al.*, 2003) and the need of high vacuum and high voltage supply for the photomultipliers, in addition to the fabrication difficulties and the high cost of those

detectors. Recently, wideband gap materials such as zinc oxide have been used in the fabrication of the UV detectors due to their wide band gap (~3 eV) (Lee *et.al.*, 2003; Chang *et.al.*, 2006; Emanetoglu *et.al.*, 2004; Balducci *et.al.*, 2005; Chiba *et.al.*, 2006; Kong *et.al.*, 2009; Al-Mumen, 2016). However, these detectors required extra work before they become commercially available.

On the other hand, dye sensitized solar cells have been extensively studies as an alternative to the traditional silicon solar cells due to its inexpensive components and easy to fabricate (Rogalski and Razeghi, 1996; Lee and Kim, 2009; Liu *et.al.*, 2010; Dürr *et.al.*, 2005). However, the lack of efficiency has limited their commercial implementation. Furthermore, dye sensitized cell was proved to be used as a photodetectors as well. This is due to its self-powered and excellent physical and chemical properties (Grätzel, 2001; Cao *et.al.*, 2011; Li *et.al.*, 2012; Wang *et.al.*, 2012; Matsui *et.al.*, 2004; Kim *et.al.*, 2006). In the following sections we will explain in detail our new fabrication steps that added to the conventional design of the dye sensitized cell to improve its properties. Additionally, we proved that this cell can be used as a practical UV detector. Several testing techniques were applied to evaluate the detector static characteristics, such as time response, sensitivity, selectivity, and waterproof, in addition to the self-power test.

2. Fabrication process of the detector

Briefly, TiO_2 nano-powder was mixed with ethanol and then sonicated for 1hr. A TiO2 layer of ~ 200 µm was deposited on the Indium Tin Oxide (ITO) glass which has dimensions of (50×50×1) mm, then was heated on a hot plate at 180 °C for 15 min to form TiO_2 electrode. The TiO_2 electrode was dipped in a dye solution (Eosin) for 15 min. Prior to combination of the two ITO glasses, a drop of electrolyte (Lugol's iodine, 2.2 % iodine and 4.4% potassium iodide) was added in between the two ITO glasses. The edges were covered by SU8 2025 photoresist as it is stable and resists most acids and solvents (Lorenz *et.al.*, 1997). In order to obtain cross-linked SU8, the device was soft baked for 2 min at 95 °C, exposed to UV light for 20 sec and hard baked at 95 °C for 2 min. After the device had cleaned by deionized (DI) water and dried, a silver paste was used to connect two wires to the ITO. Finally, a protection layer of PDMS (Polydimethylsiloxane) was spin coated on both sides of the device. Fig. 1 shows the schematic and the photo image of the device.

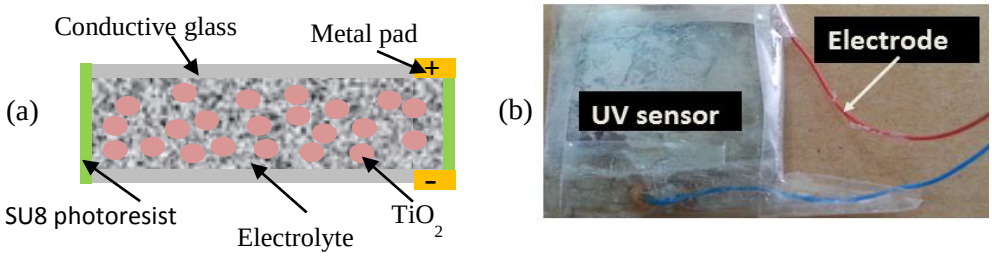


Figure (1): (a) Structure of the UV detector (b) Photo image of the detector after fabrication.

3. Testing of the detector

Basically, illuminating the fabricated device to UV light enhances electrons to escape from dye to the conduction band of the TiO_2. The lost electrons are compensated by the electrolyte. The electrons move to conductive glass and then flow through the

wire. In the following sections, the dye sensitized cell will be presented as a UV detector. The current-voltage characteristic of the detector measured at range from (-1 to 1) V (Fig. 2). At UV irradiation of wavelength of 365 nm, and intensity of 0.1 mW/cm^2, the photo current could reach 0.9 mA. This means that increasing the applied voltage to the detector from (-1 to 1) V leads to dramatically change in the photocurrent by around 3 orders of magnitude compared to the leakage current that was generated due to ambient light.

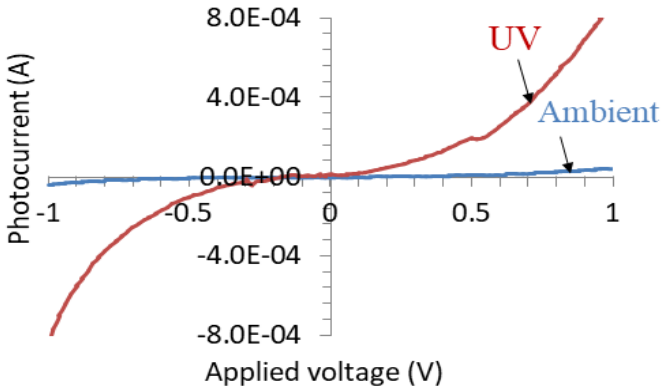
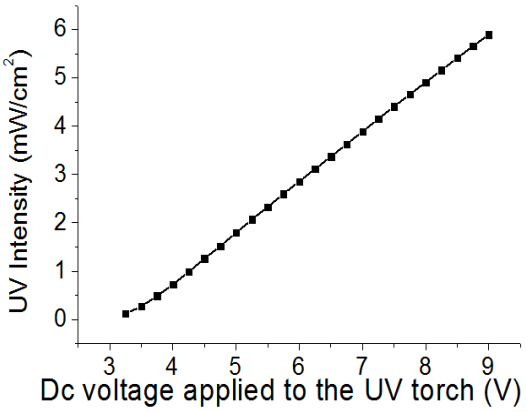


Figure (2): Electronic properties of the device in ambient and under UV illumination at λ=365 nm.

It has been reported that the responsivity of the detector is a function of photo current, the effective area of the device, and the UV irradiation (Kong *et.al.*, 2009). The responsivity of our device was calculated to be 1440 A/W, which is comparable to the reported values (Kong *et.al.*, 2009 ; Chuang *et.al.*, 2007). Principally, the higher responsivity indicates high internal photoelectric current gain. This gain can be expressed by $g=\tau\mu V_B/L$ (Sze and Ng, 2006), where τ is the mean lifetime of the charge carrier, L is the inter-electrode spacing, V_B is the applied bias, and μ is the electron mobility.

A UV Light-Emitting Diode (LED) torch with a peak wavelength of 365 nm was used in our experiment. The LED was driven by a function generator (RIGOL-G1022), which was also used to control the light intensity and to obtain both discrete (pulses) and continuous (sinewave) light signals.

Before device testing, the intensity of the LEDs torch was measured and calibrated by AB-M model 100-C UV intensity meter. The calibration curve was obtained by applying several voltage values to the LEDs torch and measuring the corresponding intensities. The calibration curve showed linear relationship (Fig. 3).



Figure(3): Calibration curve of the UV light source.

The response speed is a significant parameter which can be used to determine the property of the photodetectors. Fig. 4 shows incident light dependent current measured with a light pulse rate of 1 pulse/ 20 sec and light intensity of 0.25 mW/cm^2. It is obvious that the rise time and fall time of the detector are almost have the same values, ~ 0.1 sec, which is good compared to the other photodetector technologies (Kong *et.al.*, 2009). Additionally, since the device is encapsulated, then it would not be attacked by the oxygen of the environment. As a result, the number of trapped holes would be minimized, and then the combination between the negative and positive charge carriers would be increased, which lead to decrease in the fall time.

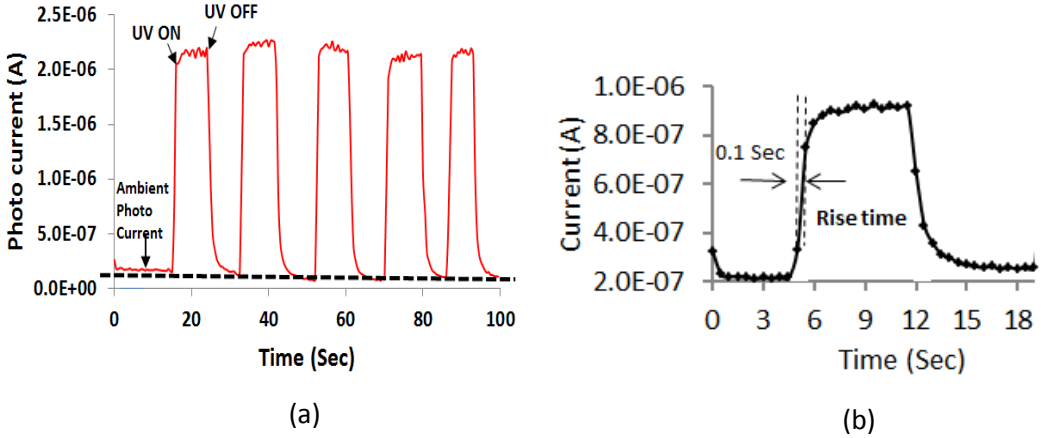
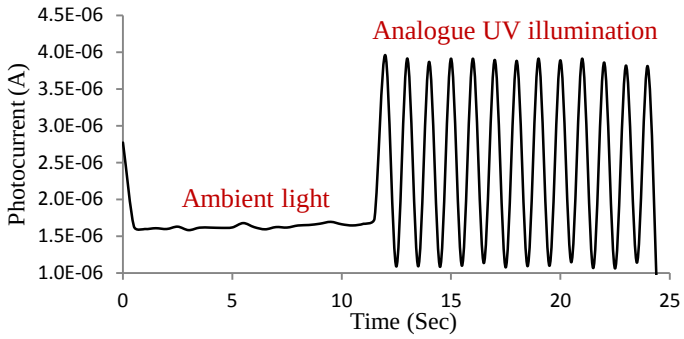


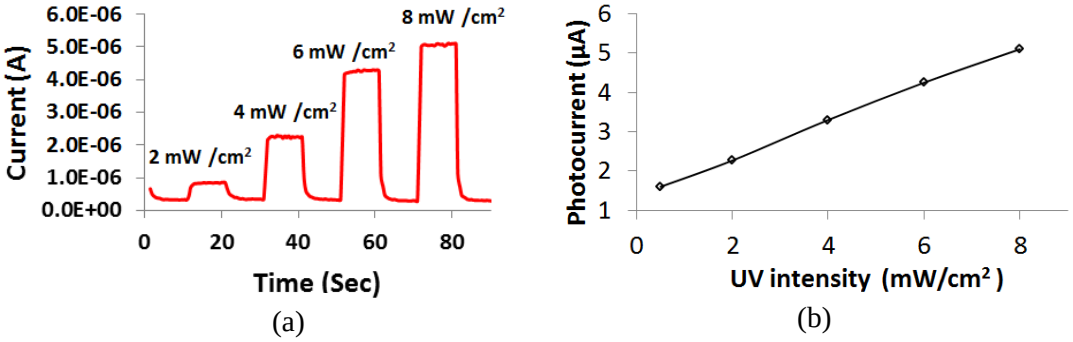
Figure 4: (a) Time response of the device to on/off light pulses. (b) Rise time of the device.

In the reported articles only discrete time (on/off) response of UV detectors has been studied. In this work, the response for continuous UV light was studied too. Sinewave light source with a low frequency 1 cycle/ 3 sec was irradiated on the detector (Fig. 5). The response observes a perfect sinewave photocurrent response with no distortion. This means that the detector has perfect response for analog as well as digital light signal irradiations.



Figure(5): Time response of the device to continuous sinewave light irradiation.

Photocurrent of the device versus incident light intensities was investigated (Fig. 6). The photocurrent measurements were carried out under 365 nm UV irradiation while the light intensity was varying from 0.1 W/cm^2 to 8 mW/cm^2. The photocurrent increases linearly with the light intensity. This linear relation suggests that the device can be used not only as a UV detector but also for precise UV measurements.



(a) (b)

Figure (6): (a) Photocurrent versus incident UV. (b) The photocurrent of the detector at different intensities.

4. Water-resist test

To explore waterproofing, the detector was tested in water (Fig. 7). Basically, in case of under-water test, the view angle of the UV detector is reduced and then partial of UV light will reach the detector (Markager and Vincent, 2000 ; Ohde and Siegel, 2003; Zibordi, 2006). Another attenuation factor is light scattering due to impurities, especially when the measurement done in unclean water. In addition to the absorption characteristic of the UV light underwater (Markager and Vincent, 2000). Therefore, it is expected decline in photocurrent compared to the in-air measurements. Our testing setup consists of a glass tank with a jacket (resemble a light isolator). Testing was done in the depth of ~30 cm. No significant difference in the time response was observed. However, attenuation in the photocurrent was recognized which can be attributed to the above reasons.

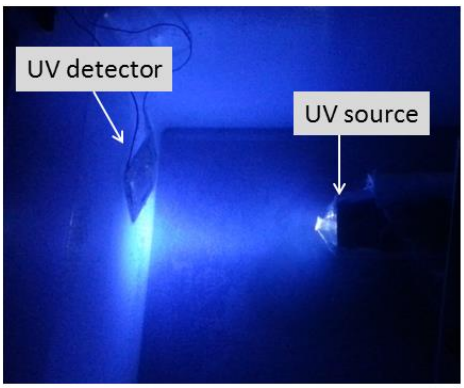


Figure (7): Testing setup for underwater measurement.

5. Detector Interfacing to Microcontroller

Once the detector is irradiated by UV, it produces a small amount of voltage, a partial of a volt, which is proportional to the UV intensity. However, this amount of voltage within the sensitivity of the Analogue to Digital Convertor (ADC), which is built-in the Microcontroller. The system was implemented using an 8-bit microcontroller running on 16 MHz and operation voltage of 5 V (as shown in Fig. 8 (a) and (b)). Neither signal conditioning nor signal processing require for interfacing the detector to the Microcontroller. Therefore, the detector was connected directly to the Microcontroller (Arduino UNO) through its 8-bit ADC and then to the analogue input port. Due to limited capacity of the memory, an external memory was connected to store the data fetching from the detector though the ADC.

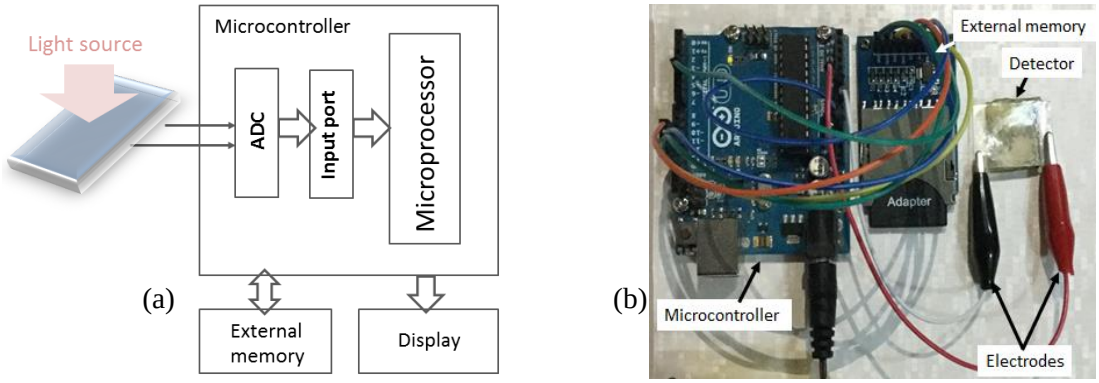


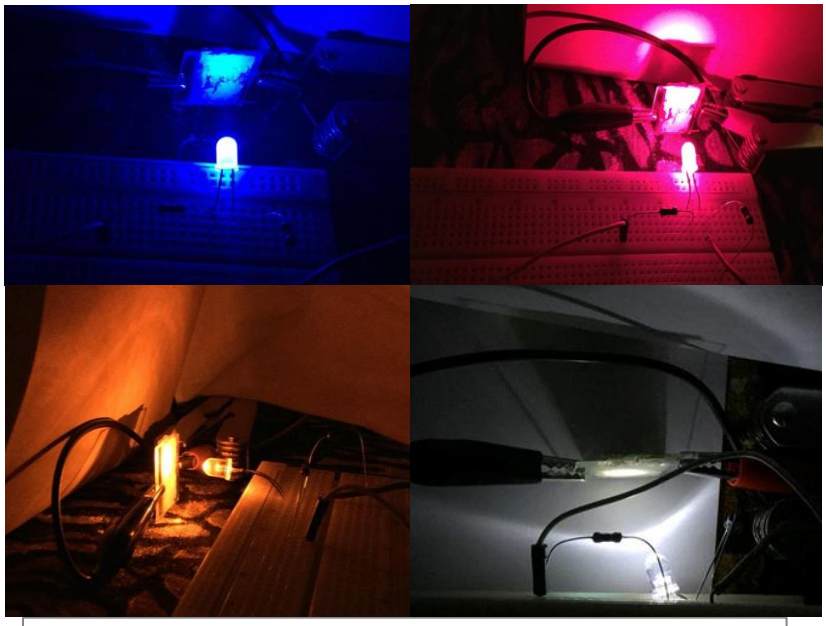
Figure (8): (a) Schematic of the sensor interfacing to the microcontroller (b) Photo image of the system.

6. Color recognition

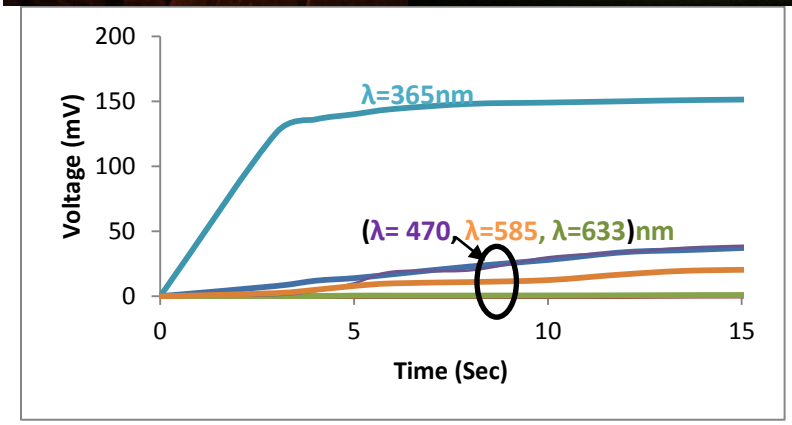
Recently, Color sensors play a significant role in a wide variety of optoelectronics applications. Typical examples includes, biomedical instruments, chemical analysis and other industrial applications (McCamy, 1992). Our device was tested to be used as a color detector. Several colors at a particular wavelength (λ) were used in our testing setup. Experimental Results showed that the detector reacts to different colors with different sensitivity and rise time. Fig. 9 (a) illustrates the detector time response to several colors (blue, red, yellow, sunlight and UV) with a wavelength of 365, 470, 585 and 633nm respectively. Fig. 9 (b) observes the values of rise time for each color. Specifically, the shortest rise time was around 1 sec, while the greatest induced voltage

achieved when the detector irradiated with a UV light. Therefore, because of the remarkable selectivity of this detector it could be used not only for UV light detection but also for recognizing colors.

(a)



(b)



(c)

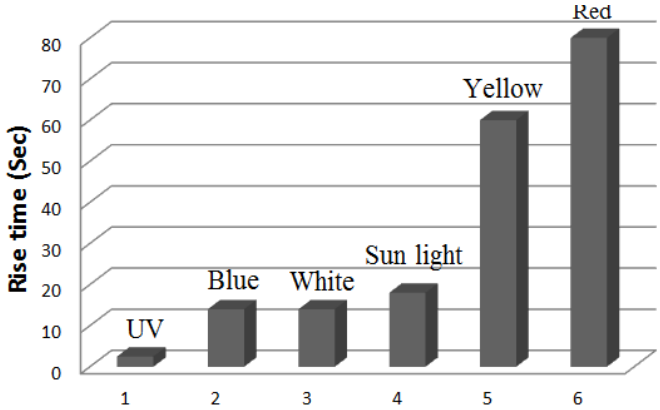


Figure (9): (a) Color testing setup. (b) Time response at various colors. Inset is the testing setup. (c) Rise time at various colors.

7. Conclusion

As a conclusion, dye sensitized cell was fabricated and tested under various conditions. The device exhibits short rise time and high sensitivity for both discrete and continuous light intensities. It also shows stable characteristic in ambient as well as underwater. The self-powered characteristic of the sensor makes the interfacing to a microcontroller so easy with no need for any intermediate electronic components such as voltage amplifier. The detector has remarkable selectivity for several light colors. Therefore, this type of photo-detectors technology seems promising towards commercial production of optoelectronic components such UV and color sensors.

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