Understanding UV Sensor Performance in ZnO TFTs Through the Application of Multivariate Analysis

Kumar, Dinesh; Gomes, Tiago; Alves, Neri; Kettle, Jeffrey

2018 IEEE SENSORS

DOI:
10.1109/ICSENS.2018.8630303

Published: 31/01/2019

Peer reviewed version

Understanding UV sensor performance in ZnO TFTs through the application of multivariate analysis

Dinesh Kumar[1], Tiago Gomes[1,2], Neri Alves[2], Jeff Kettle[1*]

[1]School of Electronics, Bangor University, Bangor, Gwynedd, LL57 1UT, Wales, UK, * Email: j.kettle@bangor.ac.uk

[2]Departamento de Física, Química e Biologia - DFQB, Faculdade de Ciência e Tecnologia, UNESP, Presidente Prudente, SP, Brazil

***Abstract*—Zinc oxide (ZnO) thin film transistors are well suited to UV sensing application because they absorb predominantly in the UV region due to the wide bandgap (Eg = 3.37 eV) and possess a large exciton binding energy (60 meV) with high radiation hardness. When operated as a transistor, many device performance parameters alter such as threshold Voltage, on-off current and channel mobility. As a result, it is to distinguish between changes in electrical performance induced by UV light and environmental effects that add noise to the sensor performance. In this work, the UV response of zinc oxide thin film transistors (ZnO TFTs) is examined using Taguchi Design of Experiment (DOE) method. By using this multivariate analysis approach, it is possible to reduce the number of calibration tests required for the sensor to accurately assess UV irradiation It is observed that different input conditions (UV power, exposure time, temperature, bias conditions) affect different TFT performance parameters more or less significantly. From the perspective of UV sensing, ON current in the saturation region appears to be the best performance parameter in a ZnO TFT for examining differences in UV exposure.**

***Keywords*— ZnO thin film transistor, ZnO TFT UV photo sensor, Radio frequency sputtering, ultraviolet**

I. Introduction

In last few years, ultraviolet (UV) light has been key in several industrial fields such as telecommunications, ozone and pollution monitoring, high temperature flame detection and missile warning systems. UV light is electromagnetic radiation with a wavelength shorter than that of visible light, but longer than X-rays, in the range 10 nm to 400 nm, and energies from 3 eV to 124 eV. The well-established semiconductor material, silicon (Si) has limited UV detecting properties because of its poor responsivity in this region. The bandgap energy of Si is 1.1eV, so costly high pass optical filters and phosphors are needed to respond to high energy photons, causing reduction in sensor efficiency and increase of dark currents [1]. By contrast, the wide bandgap (Eg = 3.37 eV) ZnO metal oxide semiconductor is promising candidate for UV detection due to its large exciton binding energy (60 meV), and superior radiation hardness [1]. ZnO-based thin-film transistors (ZnO-TFTs) have attracted much attention over the last quite a few years because of the many potentials leading to future electronic and optoelectronic applications such as realizing transparent electronics, replacing conventional amorphous-Si TFT. Furthermore, ZnO can be used in photo-detectors [2] when used with a p-type material to form a photodiode or as a resistive-sensor. Several researchers have utilised ZnO-based semiconductors as the TFT channel layer, due to their high electron mobility in the saturation region, low temperature processing and low toxicity. The electrical properties and material features of the TFT's active layer strongly affect the device's transfer characteristics. ZnO based TFTs show n-type behaviour primarily as a result of oxygen vacancies and zinc interstitials, therefore, defect density control is the key to the performance of ZnO-based TFTs [3].

II. EXPERIMENTAL

For UV sensing experiments, ZnO TFTs were used. Dry 100 nm SiO_2 substrates of size 18 mm × 18 mm were thoroughly cleaned with DI water, acetone and IPA in sonication bath for 5 minutes each, followed by drying with a jet flow of nitrogen. Further surface cleaning was conducted using argon plasma for 5 minutes.

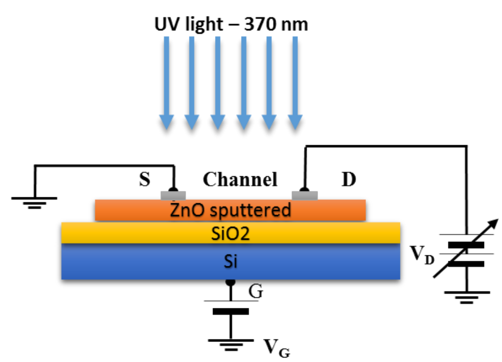

Fig. 1. A schematic cross-section of ZnO TFT biasing

ZnO TFTs were manufactured by using radio frequency (RF) sputtering technique at 75W and 1.2×10^{-2} mbar pressure. The 99.99% pure ZnO target was pre-sputtered under closed shutter for 5 min to remove contaminants from the surface. A low sputter rate of 0.05 nm/s was used for better uniformity and surface roughness of ZnO layer on substrates. ZnO layer thickness during deposition by sputtering was monitored with pre-installed thickness sensor on the sputter coater display panel. For active TFT channel 40 nm thick layer of ZnO was deposited. Annealing ZnO TFTs improves the conductivity. Therefore, after sputtering samples were annealed at 450 °C. for 1 hour. Top source/drain Aluminium (Al) electrodes were deposited by thermal evaporation using a Leybold evaporator.

In this work, a UV LED, RLS-UV370E (Purchased from Roithner Laser Technik, Austria) of wavelength of 370 nm was used for exposing ZnO channel to UV light via a light guide. The optical skin depth of UV is 50 nm at wavelengths near the peak absorption of ZnO (375nm–340nm) based upon ellipsometry data obtained in the course of this work. Ultraviolet photo sensing properties were investigated by measuring simultaneously the current-voltage (I-V) measurements for exposure conditions. Atomic force microscopy (AFM) was used to study the surface roughness of the ZnO film on SiO_2 substrates.

III. CHARACTERIZATION OF ELECTRICAL PROPERTIES

For all measurements, the electrical properties I_{on}, I_{off}, I_{on}-I_{off} ratio and mobility were extracted from transfer characteristics of TFT using equations (4) and (5).

$$I_{DS} = \mu C_i \frac{W}{2L}(V_{GS} - V_T)^2 \quad (4)$$

$$\mu_{sat} = \left(\frac{\partial\sqrt{I_D}}{\partial V_G}\right)^2 \frac{2L}{WC_i} \quad (5)$$

Where, W is channel width and L is channel length, C_i is dielectric capacitance, μ is carrier mobility, V_G applied gate voltage, V_D is drain voltage, V_{th} is the TFT threshold voltage.

Typical transfer IV characteristics of ZnO TFT under dark and after illumination of UV light are shown in figure 2. After illumination, the transistor characteristics change dramatically and consequently several of the quantifiable performance parameters are changing during the UV exposure including electron mobility in the saturation region, V_{th}, on- and off current and sub threshold swing. The physical source of the change relates to chemisorption of oxygen. In the absence of UV light, oxygen molecules can adsorb on the surface creating negatively charged ions by capturing free electrons from the n-type semiconductor, thereby create a depletion layer with low conductivity near the surface. When the sample is exposed to UV light with photon energy is more than the bandgap of ZnO, electron-hole pairs are generated [4] and the adsorbed oxygen ions combine with the holes to produce oxygen molecules, which can subsequently desorbs from the surface. Under bias, the unpaired electrons are collected at the drain; thereby an observed increase in conductivity is measured [5]. This is verified by the increasing on-current observed in figure 2. After the UV light is turned off, oxygen is readily readsorbed on the surface until equilibrium is restored. This readsorption is a slow process and significantly increases the relaxation time constant for the devices. However, this does provide a reasonable level of restoration in the UV sensor.

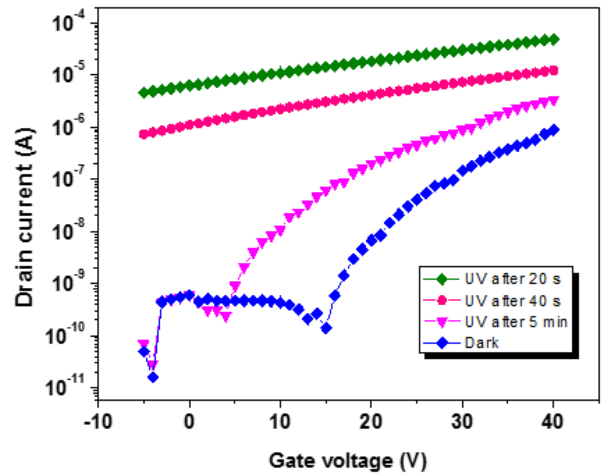

Fig. 2. Transfer characteristics of ZnO-TFT UV photo sensor under dark and after UV light with V_D=40V after excitation at 370nm.

IV. TAGUCHI ORTHOGONAL ARRAY OPTIMISATION OF UV SENSOR PERFORMANCE

Design of experiments (DOE) is an applied statistics tool and can be applied for planning a systematic experimental strategy, but, can also be used for analyzing and interpreting controlled tests that maximizes learning using a minimum of resources to evaluate the "vital few" factors that control the sensor response. DOE helps to uncover the 'significant' variables that impact upon the sensor response which is particularly important if the sensor response in adversely affected by the environment (i.e. noise) or measurement protocol. For this work, the understand the UV sensor response, an orthogonal 'L27' array was applied and analysed with the Reliasoft DOE software. Experiments were run at different factor values, called levels. Factors are the different variables which determines the functionality or performance of a product or system [6]. Each run of an experiment involved a combination of the three levels of the investigated factors, and each of the combinations is referred to as a treatment. The influence of four factors on the UV response of ZnO TFTs was investigated by Taguchi method including temperature (A), time of exposure of UV light (B), intensity of UV light (C), and voltage sweep rate per second (D) were selected as the process

TABLE I. FACTORS AND LEVELS

Factors	Unit	Level 1	Level 2	Level 3
Temperature (A)	°C	RT	40	60
Time of UV light exposure (B)	S	20	40	60
Power of UV light (C)	mW	4.8e-5	4.56e-4	1.71e-3
Voltage sweep rate (D)	V/s	0.5	2	4

parameters. Each of the factor was at three levels shown in table 1. The Taguchi experimental design of the L27 orthogonal array with four columns and 27 rows is stated in Table 1. In this case, the response can be measured from the TFT performance parameters including mobility in the saturation region, on- and off-current (I_{on}, I_{off}) and the relative change in each performance parameter can be used for multivariate analysis.

V. EXPERIMENTAL RESULTS AND DATA ANALYSIS

Multivariate analysis was used to carry out to investigate how different environmental and UV conditions affect sensor response by employing ANOVA (Analysis of Variance) to study the main effects and interactions between the variables. which environmental affects factors 'significantly' affect the selected response (i.e. mobility, drain I_{on}, I_{off}) by using hypothesis tests to find a significance level [7].

Shown in Figure 3 is the Pareto chart which ranks the main effects and interactions that impact the sensor response by considering changes in the I_{on} of the ZnO TFT. The impact of each factor is listed in rank order by considering the standardized effect of each term (i.e. factor or combination of factors). The thick blue line is the threshold value defining the significance level. If the value of the factor is higher than the significant level, then this effect is deemed significant, based upon hypothesis testing. As shown in fig. 3 power of UV light (C1; i.e. varying from between level 1 and 2) is the most significant effect and temperature of measurement (A), time of exposure of UV light (B) and interaction between factors A[1] and D[2] are also significant effects for I_{on} response.

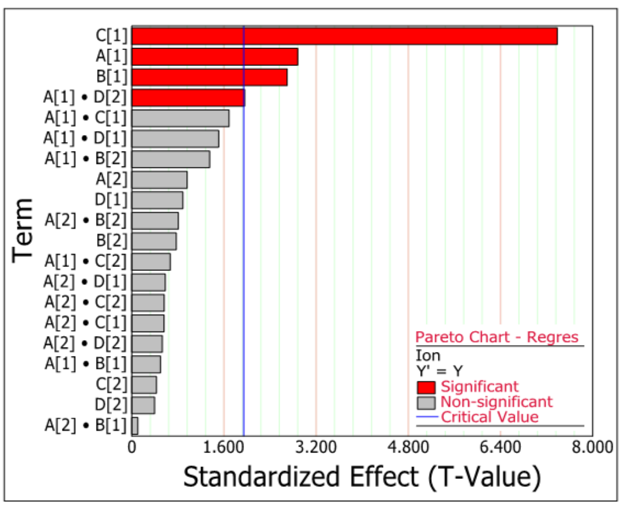

Fig. 3. Pareto Chart regression for drain on current (Ion) of ZnO TFT sensor (A: temperature during measurement, B: time of exposure of UV light, C: optical power of UV light, D: voltage sweep rate during measurement.

A secondary method for representing sensing data is shown in figure 4 which plots the fitted means i.e. the change in a performance parameter when other factors are kept constant. In this case, the impact of different UV and environmental conditions upon the saturated electron mobility is shown. Fig.4 shows that with increase in temperature of measurement (A), power of UV light (C) from low to high level the mobility increases. This is because of increase in thermally and photo generated charge carriers in channel of ZnO TFT. There is increase in mobility with increase in exposure time of UV light (B) although this appears to saturate at longer times.

One interesting conclusion from our study is that there are no significant effects for I_{off} response and this indicates that this parameter is not a good sensing measurement parameter.

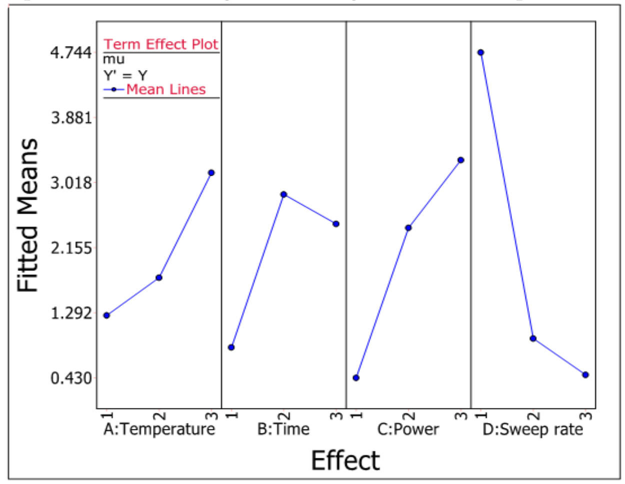

Fig. 4. Term effect plot for mobility (mu) of ZnO TFT sensor (A: temperature during measurement, B: time of exposure of UV light, C: optical power of UV light, D: voltage sweep rate during measurement

ACKNOWLEDGMENT

TG would like to thank FADESP. JK and NA would like to thank the Newton Fund for supporting the work.

REFERENCES

[1] S. P. Ghosh, K. C. Das, N. Tripathy, G. Bose, D. H. Kim, T. I. Lee, J. M. Myoung, and J. P. Kar, "Ultraviolet photodetection characteristics of Zinc oxide thin films and nanostructures," *IOP Conf. Ser. Mater. Sci. Eng.*, vol. 115, p. 12035, 2016.

[2] P. Ivanoff Reyes, C. J. Ku, Z. Duan, Y. Xu, E. Garfunkel, and Y. Lu, "Reduction of persistent photoconductivity in ZnO thin film transistor-based UV photodetector," *Appl. Phys. Lett.*, vol. 101, no. 3, 2012.

[3] Z. Pan, X. Zhao, W. Peng, X. Qi, and Y. He, "A ZnO-based programmable UV detection integrated circuit unit," *IEEE Sens. J.*, vol. 16, no. 22, pp. 7919–7923, 2016.

[4] J. Kettle, H. Waters, Z. Ding, M. Horie, G.C. Smith, "Chemical changes in PCPDTBT: PCBM solar cells using XPS and TOF-SIMS and use of inverted device structure for improving lifetime performance," *Solar Energy Materials and Solar Cells*, *141*, 139-147, 2015

[5] C. Soci, A. Zhang, B. Xiang, S. A. Dayeh, D. P. R. Aplin, J. Park, X. Y. Bao, Y. H. Lo, and D. Wang, "ZnO nanowire UV photodetectors with high internal gain," *Nano Lett.*, vol. 7, no. 4, pp. 1003–1009, 2007.

[6] D.-W. Kim, M.-W. Cho, T. Seo, and E.-S. Lee, "Application of Design of Experiment Method for Thrust Force Minimization in Step-feed Micro Drilling," *Sensors*, vol. 8, no. 1, pp. 211–221, 2008.

[7] V.Stoichkov, D. Kumar, P. Tyagi, and J. Kettle, "Multistress Testing of OPV Modules for Accurate Predictive Aging and Reliability Predictions", accepted in IEEE JOURNAL OF PHOTOVOLTAICS, DOI: 10.1109/JPHOTOV.2018.2838438