2021 18th International Conference on Electrical Engineering, Computing Science and Automatic Control (CCE). Mexico City, Mexico.
November 10-12, 2021

Genetic Algorithm-based Approach to Enhance the Performance of Gate Engineered InGaZnO UV Thin-Film Phototransistor

H. Ferhati and F. Djeffal

Abstract— **This work aims to study the role of material gate engineering (MGE) paradigm combined with Genetic Algorithm (GA) evolutionary technique in enhancing the performance of InGaZnO (IGZO) thin-film (TF) Ultraviolet (UV) phototransistor for optical wireless communication systems (OWCSs). Accurate numerical models for the optical and electrical performances of the investigated phototransistor are carried out. A new approach based on implementing GA evolutionary technique to optimize the device performance is proposed. It is found that the optimized MGE IGZO TF UV phototransistor shows enhanced current ratio of 140 dB and high responsivity of 1.3×10^2 A/W, far surpassing that provided by the conventional sensors. This is mainly attributed to GA approach and MGE aspect in modulating the channel electrical behavior leading to achieve an improved light-induced carrier transport. Therefore, promoting enhanced collection efficiency, this new approach based on introducing MGE and GA optimization technique open up promising routes for the design of efficient UV phototransistors, which are highly attractive for the advanced optoelectronic and Internet of Things (IoTs) technologies.**

Index Terms— **IGZO; gate material engineering; TFT; GA; IoT; phototransistor**

I. Introduction

As the Internet of Things (IoTs) continues to develop, extensive global optimization problems arisen in different domains involving industry, engineering, military, economics and material science [1]. Basically, conventional optimization techniques face extensive challenges to solve many real-life problems due to the fact that they can be entrapped in local optima solutions [2]. Alternatively, major research interests have been devoted to innovative artificial intelligence tools in the field of optimization [1-3]. For example, metaheuristic methods like Particle Swarm Optimization (PSO) and Genetic Algorithm (GA) proved their effectiveness for dealing with various engineering problems. The latter benefits have inspired their implementation for the expansion of optical wireless communication systems (OWCS) [4].

Phototransistor as a core sensor technology has drown a surge of research interest to develop efficient and low power consumption OWCS [5-9]. Basically, the basic idea behind this device dwells on the monolithic integration of transistor and photodetector to achieve the self-amplification property [7-11]. Several light sensors are developed basing on active regions with matched band-gap materials that can be sensitive to specific wavelengths corresponding to UV, visible and NIR irradiations [9-16]. Particularly, wide band-gap IGZO material (Eg > 3eV) has been used to elaborate three-terminal thin-film phototransistors [6], [14-16]. The latter technology has recently triggered a great deal of consideration due to its advantages like UV-light sensing capability, high carrier mobility of IGZO, gate control property, low power dissipation and high chemical stability [16]. Despite these benefits, the prepared IGZO TFT UV phototransistor shows a quite low photocurrent less than 1nA, which is explained by the ultrathin nature of the IGZO active-film and recombination effects. Researchers have proposed the incorporation of high-k gate dielectric to achieve better control over the channel [17]. Further, capping the TFT structure with several absorber materials well matching the envisaged spectral range such as perovskite and monolayered materials has demonstrated improved sensor photoresponse [6], [10-11] and [14-16]. However, these strategies require complex and costly fabrication process, shows high dark-noise owing to the existence of interfacial traps and degraded switching capabilities.

Material gate engineering (MGE) paradigm has been used to address several undesired effects associated with nanoscale transistors such as hot-carrier effect, low derived current capability and degraded switching capabilities [18-21]. Promising results were reached, thus confirming its appropriateness for the continuous downscaling according to Moor's law. Intuitively, this strategy can be used to enhance the IGZO thin-film UV phototransistor through reducing the recombination losses in the device sensitive layer. To the best of our knowledge, no design approach based on MGE paradigm combined with GA optimization technique was proposed to achieve better sensing performances. The present work aims to investigate the role of MGE aspect assisted by GA approach in improving the IGZO TF UV phototransistor

H. Ferhati is with the Advanced Electronics Laboratory (LEA), University of Batna 2 and ISTA, University of Larbi Ben M'hidi, Oum El Bouaghi, Algeria. (ferhatihichem@gmail.com)
F. Djeffal is with the Advanced Electronics Laboratory (LEA), Department of Electronics, University of Batna 2, Algeria (faycaldzdz@hotmail.com).

performances. The optimized MGE UV-sensor demonstrates high-responsivity and superior ON-to-OFF current ratio in wide working voltage window. Therefore, the optimized UV sensor allows reaching enhanced performances at low-cost, making it suitable for OWCSs.

II. Device Structure, Numerical Models and Optimization Procedure

In this section, we describe the proposed IGZO thin-film UV phototransistor based on MGE aspect. In addition, the introduced numerical models governing the device transport mechanism and the optical behavior are presented.

A. MGE IGZO thin-film UV phototransistor structure

Fig.1 shows the structure configuration of the proposed IGZO TF UV phototransistor with dual material gate. The cornerstone of the studied device resides on inserting two dissimilar gate regions, respectively described by different work-function values φ_{mg1}, φ_{mg2}. From Fig.1, we can see that the analyzed UV sensor based on MGE paradigm consists of two elementary phototransistors related in series with L_1 and L_2 are their channel length. The phototransistor channel with length L is designed by IGZO thin-film acting also as photosensitive layer to the incident UV photons. Besides, d_{IGZO} is the IGZO channel thickness and d_{SiO2} denotes the SiO_2 thickness. V_{gs} and V_{ds} are respectively the applied gate and drain voltages. The proposed device is exposed to UV light with specific wavelength value of 365 nm. Table.1 recapitulates the design parameters values used for the device simulation. To assess the device regarding the working voltage range, the applied gate bias is varied from -10 V to 20 V with the step of 0.5 V. By illuminating the device, e/h pairs are generated in the IGZO layer. The latter carrier are separated by the electric field induced by applied voltages, thereby collected at the drain electrode. This leads to achieve the UV photoresponse of the phototransistor.

B. Numerical models

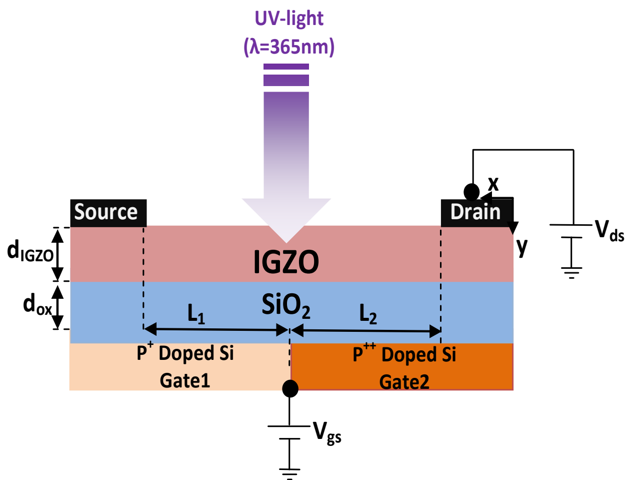

Fig. 1. Structure of the analyzed IGZO FT UV phototransistor with MGE paradigm.

TABLE I
RECAPITULATION OF CONFIGURATION PARAMETERS FIXED DURING THE NUMERICAL INVESTIGATION.

Parameter	Symbol	Value
Channel length	L	100 nm
Oxide thickness	d_{ox}	40 nm
First Gate workfunction	ϕ_{gm1}	4.5 eV
Second Gate workfunction	ϕ_{gm2}	(4.5-5.1) eV
IGZO thickness	d_{IGZO}	20nm
Gate voltage	V_{gs}	(-10-20) V
Drain voltage	V_{ds}	1V

In this subsection, we describe the adopted models in the ATLAS simulator. Essentially, the most accurate simulation framework requires being as closer to the device natural behavior, signifying that a lots of physical phenomena must be accounted. The sensor numerical simulations are done by utilizing SILVACO device simulator (2D-ATLAS module) [22]. In this context, it paves the way to the accurate modeling of several nanoscale and complicated transistor structures [18-22]. The device transport mechanism is based on the drift-diffusion model. The Shockley-Read-Hall recombination model is included through SRH parameter. Besides, the use of MGE aspect can alter the channel electric field profile. Accordingly, FLDMOB and CONMOB statements are incorporated in the numerical model, enabling the introduction of high field velocity saturation related to parallel electric field and carrier mobility, respectively. On the other hand, the device optical properties are modeled by extracting the absorbance of the IGZO thin-film via 2-D FDTD technique presented in Luminous Module. This technique allows reproducing the propagation of the UV electromagnetic wave over the investigated $IGZO/SiO_2$ structure. Therefore, the later numerical method is exploited to solve the spatial and temporal derivatives, which are given by the following formulas

$$\frac{\partial H_x}{\partial t} = \frac{1}{\mu}\left[\frac{\partial E_z}{\partial y} - \left(M_s + \sigma^* H_x\right)\right] \tag{1}$$

$$\frac{\partial H_y}{\partial t} = \frac{1}{\mu}\left[\frac{\partial E_z}{\partial x} - \left(M_s + \sigma^* H_y\right)\right] \tag{2}$$

$$\frac{\partial E_z}{\partial t} = \frac{1}{\mu}\left[\frac{\partial H_y}{\partial x} - \frac{\partial H_x}{\partial y}\left(J_s + \sigma E_z\right)\right] \tag{3}$$

978-1-6654-0029-9/21/$31.00 ©2021 IEEE

where, H_x, H_y and E_z are the magnetic fields along the x, y directions and the electric field in the z axe, respectively, σ^* denote the equivalent magnetic loss, μ is the permeability, M_s and J_s represent the equivalent magnetic and the electric current densities, respectively and σ is the IGZO electric conductivity.

Afterwards, the absorbance of the investigated structure is estimated by the following formula

$$A(\lambda)=\frac{\int_V \frac{1}{2}\left|\vec{E}_z(\vec{r})\right|^2 \omega\varepsilon_0\varepsilon_i''(\lambda)dV}{\int_S \frac{1}{2}\mathrm{Re}\left\{\vec{E}_z(\vec{r})\times\vec{H}^*(\vec{r})\right\}dS} \quad (4)$$

where ε_i'' is the imaginary part of the complex materials dielectric constant and ε_0 refers to the permittivity of the vacuum, $\vec{H}^*$ represents the complex Magnetic field conjugate.

C. GA optimization approach

The exhaustive study of light-matter interaction mechanisms in oxide materials combined with dielectric media is a key subject to ultimately identify the device geometry allowing an enhanced light-absorption capability for practical sensing applications. In this viewpoint, overcoming severe optical losses using appropriate design parameters to achieve high absorbance is useful for several devices such as optical antennas, photodetectors, phototransistors, and even light-emitting diodes. In order to assess this hypothesis, we suggest the implementation of a global optimization approach based on Genetic Algorithm (GA) evolutionary computation method to maximize the absorbance over UV spectral range. The latter metaheuristic technique has demonstrated its usefulness to deal with extensive optimization problems found in several fields including nanoelectronics, computational science and optoelectronics. Despite these benefits, the execution time of the GA is higher than PSO, and the convergence is slower. GA is a nature-inspired iterative global search technique based on probabilistic approach that imitates evolution processes by executing specific genetic operators including selection, crossover, and mutation. It randomly generates an initial population with a fixed size involving a set of design variables. The solution is evaluated by defining a fitness function relative to the optimization problem. In our case, the objective function is introduced to maximize the derived current capability (I_{lum}) under lightening and the absorbance of the $IGZO/SiO_2$ structure, which can be represented by the following expression

$$Fitness\ (X)=\frac{1}{A(X)}+\frac{1}{I_{lum}(X)} \quad (5)$$

where the design parameters vector is given by $X=(\varphi_{mg1},\varphi_{mg2},d_{sio2},d_{IGZO},L_1,L_2)$.

The stall generation and the population size of the GA computation approach are respectively 800 and 20. Fig. 2 describes the proposed optimization procedure based on combining 2D-FDTD method and GA evolutionary computation technique.

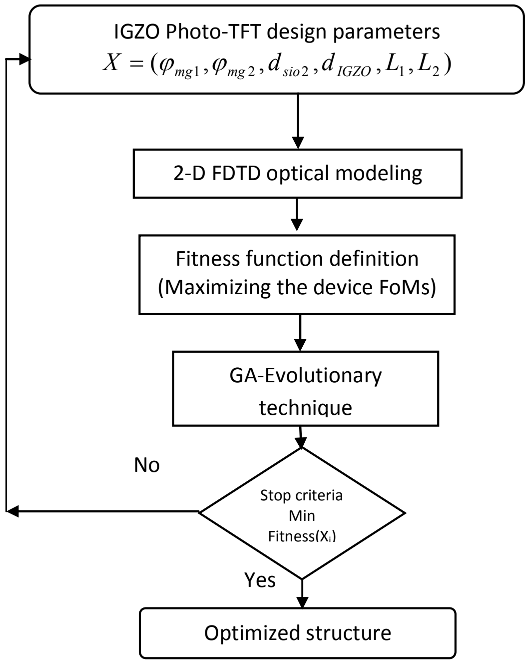

Fig. 2. The proposed approach based on FDTD computation and *GA* evolutionary technique.

III. RESULTS AND DISCUSSIONS

Fig.3 depicts I_{ds}-V_{gs} characteristics IGZO TF UV phototransistor obtained from the numerical modeling and the experimental results presented in [2] compared to that of the proposed structure involving MGE aspect for V_{ds}=1V in darkness and under UV-irradiation. Firstly, it can be noticed

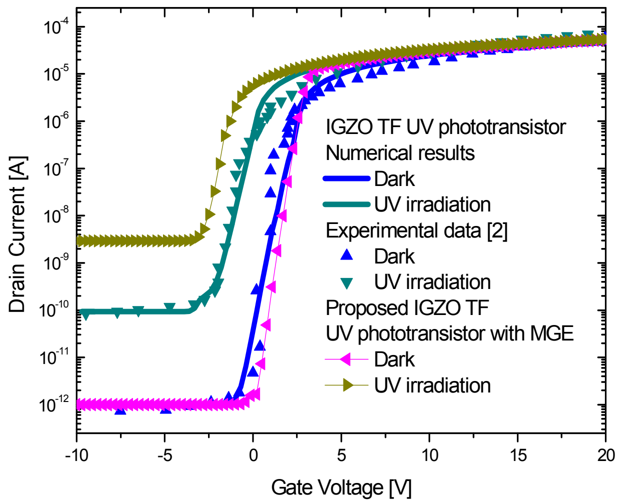

Fig. 3. I_{ds}-V_{gs} curves of the IGZO FT UV sensor under dark and UV illumination and that of the proposed sensor involving MGE aspect with L=100µm, W=10^3 µm d_{IGZO}=20nm and V_{ds}=1V.

from the latter figure that the numerical data and experimental ones agrees well, thus proving the effectiveness of the introduced numerical modeling approach.

On the other hand, it is obvious that the proposed device with MGE paradigm shows a high photocurrent as compared to the traditional device. Besides, it displays a positive threshold voltage shift, leading to reduce the OFF current and enlarge the operating voltage window. These benefits are mainly attributed to the MGE, which modulates the channel electric field distribution from the source to drain direction. This allows extending the photo-induced carrier diffusion length and thereby enhancing their collection through avoiding recombination effects.

Tto show the impact of the MGE strategy on the performances of the Photo TFT, Fig.4 illustrates the variation of the current ratio against gate voltage for different gate work-function configurations obtained from numerical simulations. This figure highlights the merit of the adopted MGE in improving the sensor performances, showing a high current ratio exceeding 129 dB. This indicates the improved photo-sensing characteristics of the proposed IGZO TF UV phototransistor. More importantly, the analyzed sensor with MGE demonstrates a high I_{ON}/I_{OFF} ratio in wider operating voltage window as compared to the conventional structure. This advantage is mainly due to the introduced MGE aspect on the device threshold voltage, where altering the gate properties in the vicinity of the drain side enables shifting the threshold voltage to positive values. This leads to achieve improved collection efficiency and maintains a very low dark current. Fig.5 depicts the variation of the phototransistor responsivity as a function of the gate work-function value near the drain region (φ_{mg2}) with V_{gs}=-0.5 V, V_{ds}=1 V and λ=365nm. We can see from the obtained numercal results that the responsivity values raises with increasing φ_{mg2} to reach its highest value for φ_{mg2} =4.9 eV and afterwards saturates with slight decrease for further superior values. This behavior is ascribed to the complex potential distribution in the channel when MGE is included. In other words, the determination of the suitable MGE configuration allowing the appropriate electric field profile that could bridge the gap between enhanced carrier separation and improved channel transport mechanism properties seems extremely complex. It can be also noticed

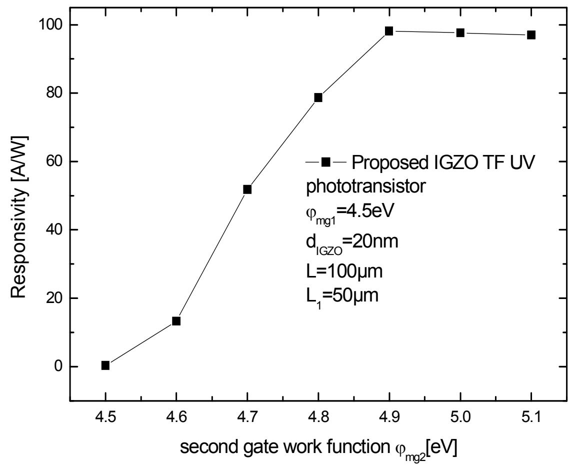

Fig. 5. Variation of device responsivity as a function of φ_{mg2} for the analyzed IGZO FT UV phototransistor with L=100µm, W=10^3 µm d_{IGZO}=20nm, L_1=50µm, λ=365nm, V_{gs}=-2V and V_{ds}=1V.

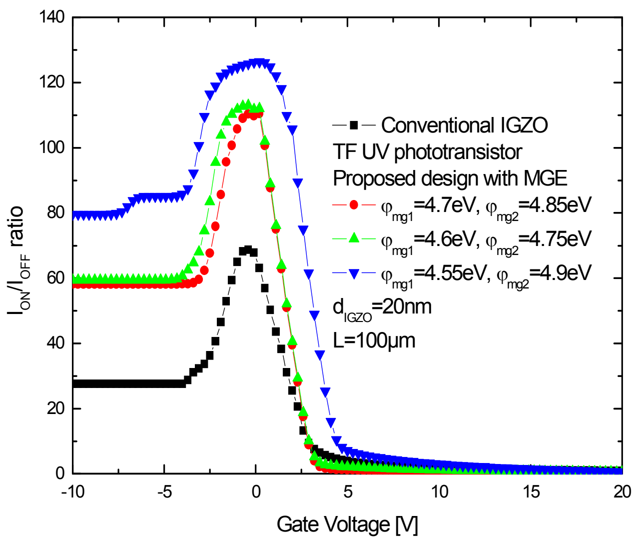

Fig. 4. I_{ON}/I_{OFF} ratio versus V_{gs} for IGZO FT UV phototransistor with various MGE configurations and the traditional structure with L=100µm, W=10^3 µm d_{IGZO}=20nm, L_1=50µm, λ=365nm and V_{ds}=1V.

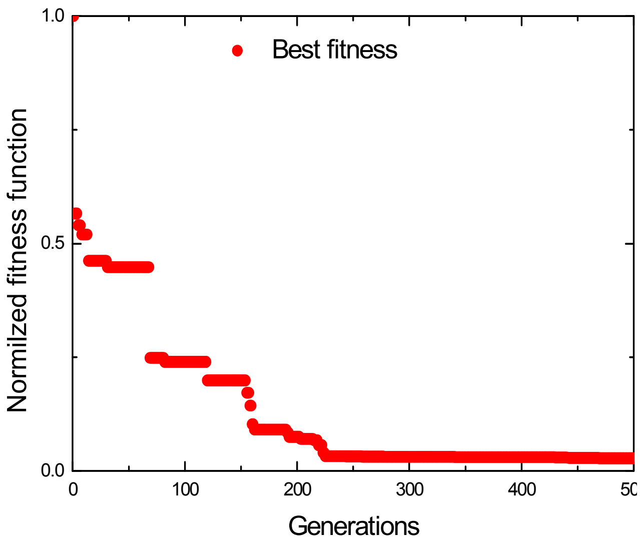

Fig. 6. Normalized fitness functions versus the GA generation number.

TABLE II
PERFORMANCE COMPARISON BETWEEN THE PROPOSED IGZO FT UV PHOTOTRANSISTOR BASED ON MGE PARADIGM AND A VARIETY OF NEWLY DEVELOPED IGZO-BASED PHOTOTRANSISTORS

IGZO Photo-TFT designs	I_{ON}/I_{OFF} ratio (dB)	Responsivity (A/W)	Detectivity (Jones)	Ref.
IGZO Photo-TFT	46	0.08	1.3×10^{10}	[10]
IGZO/$CH_3NH_3PbI_3$	138.8	61	9.4×10^{10}	[11]
InGaZnO/Aligned-SnO_2 Nanowire	114	8.3	-	[15]
IGZO TFT with T_2O_5 gate dielectric	100	6.4	-	[17]
Optimized IGZO with MGE aspect	139	135	7.2×10^{13}	This work

from Figures 4 and 5 the complex photosensing characteristc when involving the effect of MGE aspect, where selecting the appropriate work-function valus as well as the device geometry is extremely challenging. For this reason, we have implimented GA-based computation to identify the suitable geometry and MGE configuration providing the highest FoM parameters as it is throughly desscussed in section.2.c. Fig.6 shows the evolution of the fitness function as against the generation number of GA. After 500 generations, an excellent stabilization is reached, thus inffering the succussful minimization of the objective function and therby the maximization of the absorbance and the photocurrent. The optimized design parameter vector of the investigated Photo-TFT based on MGE is given by $X = (4.6eV, 4.95eV, 84nm, 21nm, 100\,\mu m, 62\,\mu m)$. The obtained FoM parameters from numerical simulations of the optimized MGE IGZO TFT UV phototransistor and that of the developed UV sensors reported in several published works [10-11], [15] and [17], are summerized in Table.2. The latter performance comparison showcases the capability of MGE paradigm and GA optimization procedure for outperforming the sensor performances.

IV. CONCLUSION

This paper presents the numerical investigation of a novel IGZO TF UV phototransistor based on MGE aspect. Numerical models are carried out for the simulation of the device optoelectronic behavior, showing the ability for reproducing the experimental data. The impact of MGE on the UV phototransistor performances is analyzed. The role of GA approach in boosting up the device performance is demonstrated. It is revealed that the optimized design outperforms the device in terms of sensing characteristics, UV photoresponse and dark-noise properties. In this context, the optimized IGZO TF UV phototransistor with MGE shows a high current ratio of 129 dB with a high relative improvement of 105 %. This benefit is ascribed to the optimization procedure leading to promote enhanced carrier transport and improved collection of photo-induced e/h pairs in the IGZO channel. Therefore, these fascinating properties of such IGZO TF UV phototransistor allow it to be promising for high-performance OI systems.

REFERENCES

[1] E. Aarts and J. K. Lenstra, editors. Local Search in Combinatorial Optimization. John Wiley & Sons, Inc., 1997.

[2] E. Alba and M. Tomassini, "Parallelism and evolutionary algorithms," IEEE Transactions on Evolutionary Computation, vol.6, pp.443-462, 2002.

[3] F. Djeffal, S. Guessasma, A. Benhaya, M. Chahdi, "An analytical approach based on neural computation to estimate the lifetime of deep submicron MOSFETs," Semiconductor Science and Technology, vol.20, pp. 158–164, 2005.

[4] M. D. Higgins, R. J. Green, and M. S. Leeson, "A Genetic Algorithm Method for Optical Wireless Channel Control," Journal of Lightwave Technology, vol. 27, pp. 760-772, 2009.

[5] W. Ouyang, F. Teng, J.-H. He, X. Fang, "Enhancing the Photoelectric Performance of Photodetectors Based on Metal Oxide Semiconductors by Charge-Carrier Engineering," Adv. Funct. Mater., vol. 29, pp.1807672, 2019.

[6] H-J. Na et al. "A visible light detector based on a heterojunction phototransistor with a highly stable inorganic $CsPbIxBr_3$_x perovskite and In–Ga–Zn–O semiconductor double-layer," Materials Chemistry C, vol.7, pp. 14223, 2019.

[7] A. H. Atabaki, et al, "Integrating photonics with silicon nanoelectronics for the next generation of systems on a chip," Nature Photonics, vol.556, pp. 349–354, 2018.

[8] H. Xu, J. Wu, Q. Feng, N. Mao, C. Wang, J. Zhang, "High responsivity and gate tunable graphene MoS_2 hybrid phototransistor," Small, vol.10, pp.2300-2306, 2014.

[9] H. Ferhati, F. Djeffal and N. Martin, "Highly improved responsivity of self-powered UV-Visible photodetector based on TiO_2/Ag/TiO_2 multilayer deposited by GLAD technique: Effects of oriented columns and nano-sculptured surface," Applied Surface Science, vol.529, pp. 147069, 2020.

[10] J. Yu, et al, "High-Performance Visible-Blind Ultraviolet Photodetector Based on IGZO TFT Coupled with p−n Heterojunction," ACS Applied Material Interfaces, vol.10, pp. 8102−8109, 2018.

[11] Y. J. Tak, D. J. Kim, W-G. Kim, J. H. Lee, S. J. Kim, J. H. Kim and H. J. Kim, "Boosting Visible Light Absorption of Metal-Oxide-Based Phototransistors via Heterogeneous In–Ga–Zn–O and CH3NH3PbI3 Films," ACS Applied Material Interfaces, vol. 10, pp. 12854-12861, 2018.

[12] T. Bentrcia, F. Djeffal, and A. Benhaya, "Continuous analytic I-V model for GS DG MOSFETs including hot-carrier degradation effects," Journal of Semiconductors, vol.33, pp. 014001, 2012.

[13] C. Wang, Xi. Zhang and W. Hu, "Organic photodiodes and phototransistors toward infrared detection: materials, devices, and applications," Chem. Soc. Rev., vol. 49, pp. 653-670, 2020.

[14] J. Yang, et al, "MoS2–InGaZnO Heterojunction Phototransistors with Broad Spectral Responsivity," ACS Applied Material Interfaces, vol. 8, pp. 8576–8582, 2016.

[15] X. Liu, et al, "Transparent, High-Performance Thin-Film Transistors with an InGaZnO/Aligned-SnO_2-Nanowire Composite and their Application in Photodetectors," Advanced Materials, vol. 26, pp. 7399–7404, 2014.

[16] X-L. Wang, Y. Shao, X. Wu, M-N. Zhang, L. Li, W-J. Liu, D. W. Zhang and S-J. Ding, "Light response behaviors of amorphous In–Ga–Zn–O thin-film transistors via in situ interfacial hydrogen doping modulation," RSC Advances, vol. 10, pp. 3572, 2020.

[17] T. H. Chang, C. J. Chiu, W. Y. Weng, S. J. Chang, T. Y. Tsai, and Z. D. Huang, "High responsivity of amorphous indium gallium zinc oxide phototransistor with Ta_2O_5 gate dielectric," Applied Physics Letters, vol. 101, pp. 261112, 2012.

[18] Z. Ghoggali and F. Djeffal, "Analytical analysis of nanoscale fully depleted Double-Gate MOSFETs including the hot-carrier degradation effects," International Journal of Electronics, vol. 97, pp. 119–127, 2010.

[19] A. Goel, S. Rewari, S. Verma and R. S. Gupta, "Shallow Extension Engineered Dual Material Surrounding Gate (SEE-DM-SG) MOSFET for improved gate leakages, analysis of circuit and noise performance,"

AEU-International Journal of Electronics and Communications, vol.19, pp. 152924, 2019.

[20] Z. Ghoggali and F. Djeffal, "Analytical analysis of nanoscale fully depleted Double-Gate MOSFETs including the hot-carrier degradation effects," International Journal of Electronics, vol.97, pp. 119–127,2010.

[21] M. A. Abdi, F. Djeffal, Z. Dibi, and D. Arar, "A two-dimensional analytical subthreshold behavior analysis including hot-carrier effect for nanoscale gate stack gate all around (GASGAA) MOSFETs," Journal of Computational Electronics, vol.10, pp. 179–185, 2011.

[22] Atlas User's manual, SILVACO TCAD, 2012.