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The Vacancy Pool Model for Amorphous In-Ga-Zn-O Thin-Film Transistors

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ABSTRACT In this paper, the reaction rate of oxygen vacancy (V_O) by the derivatives of threshold voltage (Vth) in the amorphous indium–gallium–zinc oxide thin-film transistors under light pulses with altering duty ratios is investigated. More importantly, after collecting and analyzing a lot of experimental results, a comprehensive model named V_O pool is proposed. The proposed model can more universally describe the characteristic of V_O reacting to the light and its degradation behavior under various kinds of stress condition.

INDEX TERMS Amorphous indium gallium zinc oxide (a-IGZO), thin-film transistors (TFTs), reaction rate, illumination effect, multiple-pulse illumination, response time, oxygen vacancy.

I. INTRODUCTION

Recently, metal oxide semiconductors have been promised for the next generation of transparent display industry due to many advantages such as high electron mobility, low off current [1], [2], low cost process temperature, and good transmittance. Among metal oxide-based materials, amorphous Indium-Gallium-Zinc-Oxide (a-IGZO) thin-film transistors (TFT) is the most attractive channel material, because the larger mobility than a-Si, better uniformity than LTPS, high on/off ratio, and the highly transmittance over 90% due to its wide band gap (∼3 eV) in visible light (400–700 nm), and so on. Owing to these good properties, a-IGZO TFTs open up to new applications such as transparent electronics [3], flexible electronics [4], [5], and photo sensors [6], [7].

Although a-IGZO TFTs have many advantages, the significant electrical instability under bias stress and light illumination is observed. Many papers reported threshold voltage shift (ΔVth) and mobility change after illumination [2], [8]–[12]. The different models were proposed to depict the degradation behavior of TFTs under various stress conditions involving light intensity, temperature, bias stress [13]–[19]. In our previous studies, we proposed a reaction model to describe the different reaction rate of oxygen vacancy (V_O) reacting with the light pulses [20]–[23]. Even though all the deterioration behaviors under all kinds of stress conditions are similar, the reaction rates of them are too diverse to be pictured in a unified expression. In this paper, we attempt to propose a representative model to interpret the diverse degradation characteristics of the stressed a-IGZO TFTs.

To verify the proposed model, the broad stress conditions in light intensity, gate bias, light pulse of period, and light pulse of duty cycle are applied to the a-IGZO TFTs. In this study, the devices are subject to the same fabrication process and measurement method, which are described in our previous papers [20]–[24]. Based on the previous research, oxygen vacancies reacting with the light-induced electron hole pairs play the leading role in ΔVth [2], [8]–[10], [18]. Therefore, the time differential of ΔVth is employed to investigate the reaction rate of V_O. We expect the proposed model to well explain the results and give an insight into the behaviors of V_O in a-IGZO TFTs.

II. THE RESPONSE TO LIGHT PULSES WITH DIFFERENT DUTY RATIOS

A. THE REACTION RATE IN CYCLES OF LIGHT PULSES

The reaction rates in Vth can be represented by the derivatives of Vth versus time [23]. Fig. 1 overlaps the curves clipped from the dark intervals between light pulses of

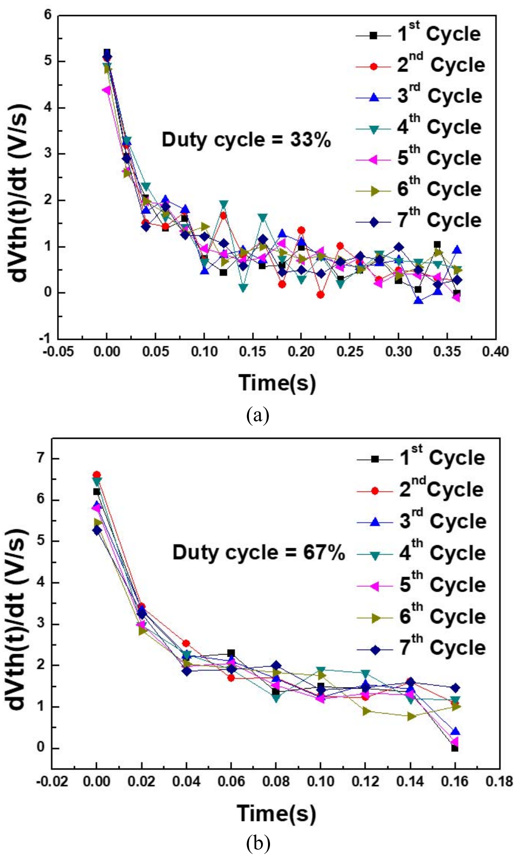

FIGURE 1. Reaction rates of *V*th in the dark intervals between light pulses with duty ratio of (a) 33% and (b) 67%.

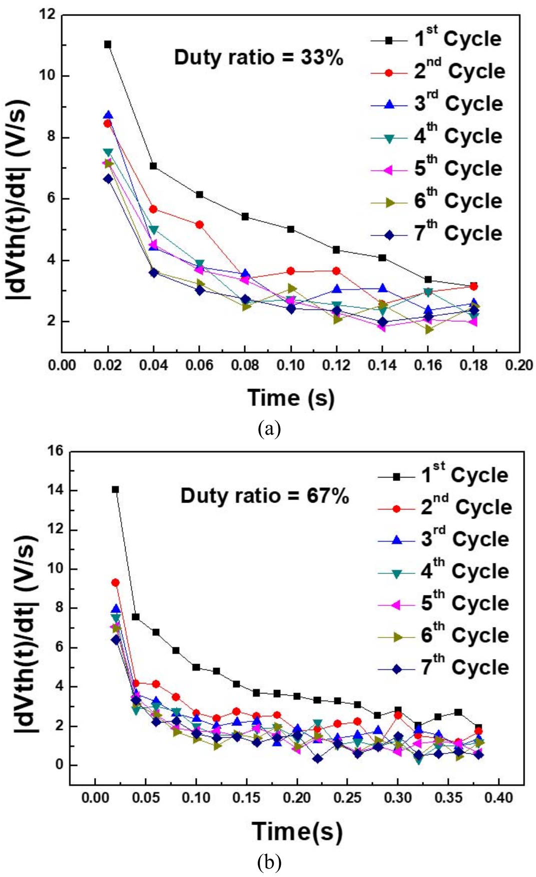

FIGURE 2. Reaction rates of *V*th in the intervals under light pulses with duty ratio of (a) 33% and (b) 67%.

20,000 Lux and 1.67 Hz for several cycles. The data plotted in Fig. 1(a) and (b) are with duty ratios of 33% and 83%, respectively. As can be seen, the reaction rates in many cycles are identical, which reconfirms our previous work [23].

For the intervals under light, the rates are depicted by the absolute value of the derivative of *V*th versus time and plotted in Fig. 2. Here, the negative shift of *V*th is happened and attributed to the domination of positively charged V_O (V_O^{2+} or V_O^{+}) instead of electron trapping at the a-IGZO/ gate insulator (GI) interface [25]. We can see that the reaction rate is relatively large in the first few cycles and converges thereafter, which is also consistent with our previous work [23]. The temporally higher reaction rates in the beginning can averaged out with the convergent ones for the further analysis in the following section.

B. LEVERAGE OF THE DUTY RATIO ON THE REACTION RATE

From Fig. 1 and 2, the average reaction rates could be obtained by the sum of peak value in each cycle divided by the number of cycles. The average reaction rates in the parts under and between the light pulses with respect to the duty ratio are plotted in Fig. 3(a) and 3(b), respectively. Besides, the error bar is also plotted to examine the accuracy of the average reaction rate. From figures, the concave upward curves are observed. According to our previous study [23], the observed reaction rate of V_O is strongly related to the time of measurement. As duty ratio is small, the duration of illumination is accordingly short. Thus, only those faster V_O can react adequately and then recover quickly enough to be re-excited again. On the other hand, when duty ratio is high, the dark interval is too short for the slower V_O to recover and then react when the next light pulse comes. For the duty ratios at both ends, the faster V_O dominate the reaction rate, because the slower V_O are excluded from the measurement. In the case of 50% duty ratio, the balanced intervals of light and darkness allow the slower V_O to involve, and thus the slowest reaction rate happens. This phenomenon reveals that the reaction rates of V_O in a-IGZO spread differently.

III. THE PROPOSED MODEL TO DESCRIBE THE REACTION AND DISCUSSION

In our previous research [20]–[23], a fitting formula had been proposed to describe the change of drain current (ΔI_D) under illumination in short and long term. More importantly, with more fitting terms, the accuracy of fitting can be better, which reveals the reaction contained by several reaction rates of Vo [23]. Interestingly, the similar results are reported in the study of the light effect on hydrogenated amorphous silicon (a-Si:H) to represent the various types of defect [26], [27].

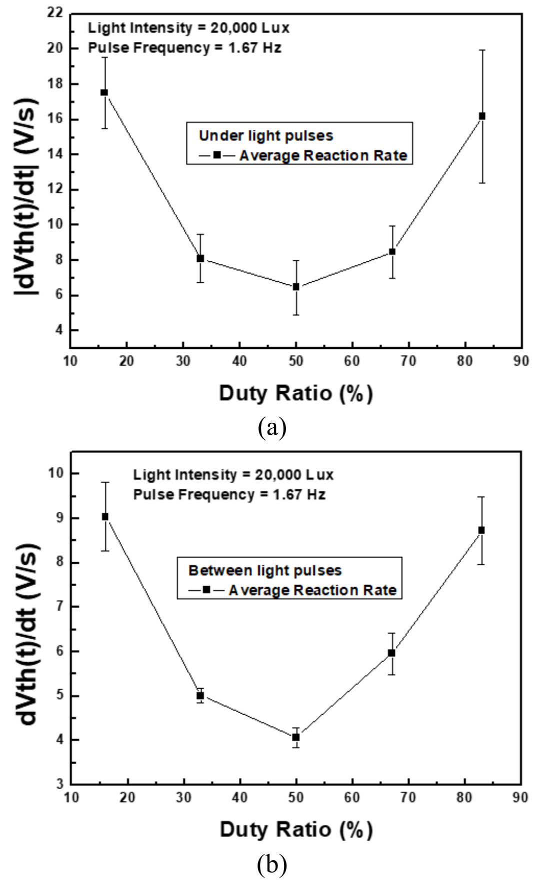

FIGURE 3. The average reaction rate with respect to duty ratio in the parts (a) under and (b) between the light pulses.

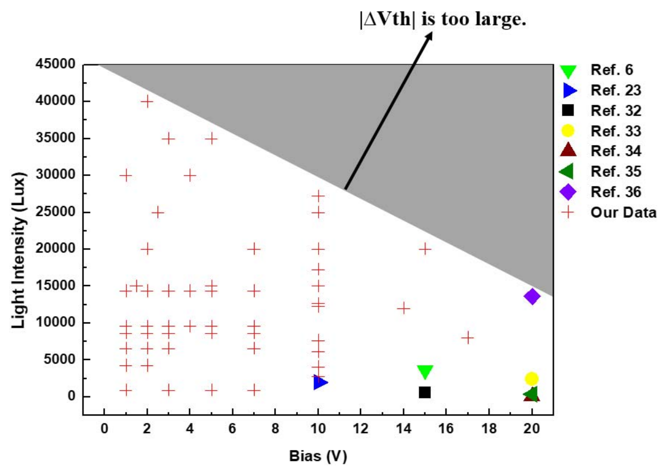

FIGURE 4. The light intensity versus bias.

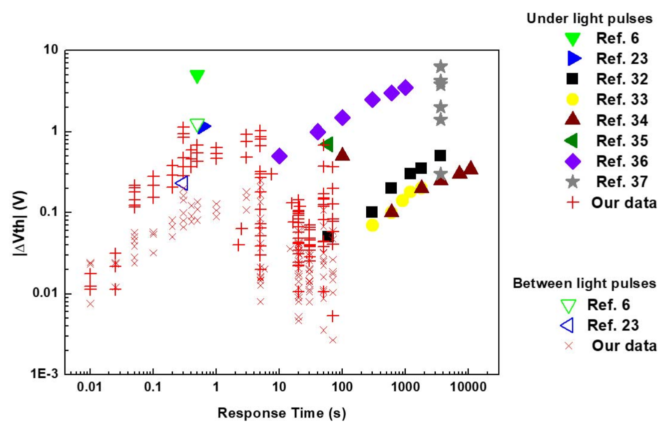

FIGURE 5. Δ*V*th versus response time under different stress condition.

Furthermore, Winer and Powell *et al.* reported these defects with dangling-bond, caused ΔVth, are in different energy states and the defect pool model was proposed to interpret the degradation [28]–[30]. However, unlike a-Si TFTs, the repeatability of experimental results is hardly achievable for a-IGZO TFTs. It is highly related to the process of reaction and recovery involving different reaction rate of Vo. With the similarity and discrepancy, a vacancy pool model in a-IGZO is presented by considering all the features we observed.

A. PROPOSING A VACANCY POOL MODEL

To provide a more comprehensive impression for the diverse degradation behaviors of a-IGZO under various duration of illumination, a new model named as "vacancy pool" is proposed. The word pool implies that V_O in a-IGZO are so many and various that they can have different reaction rates distributing over a very wide range. The fitting parameters had been well discussed in detail in our previous reports [20]–[23], [31]. We found the number of reacting V_O was dependent on the light intensity. Moreover, the strong correlation between the characteristic time constant Tau and stress time hints the diversity of the reaction rate can be correspondingly observed by the experiments in the time of interest [22], [23]. In each experiment, measurement time is fixed, and ΔVth reflects only a part of V_O in vacancy pool. Those Vo reacting relatively fast are considered as initial state, while those slower Vo have no chance to get involved. To justify the proposed model, we need to give the overall picture of the rate Vo reacting to the light.

B. PICTURING THE PROPOSED MODEL

Many experimental conditions of light intensity and bias are collected from several references [6], [23], [32]–[37] and our experiment and plotted in Fig. 4. In the gray region of upper right corner, ΔVth is too large to be observed under the strong light intensity and high bias. Using the results from those collected experiments in Fig. 4, ΔVth versus response time are plotted in Fig. 5. The response time is the duration when *Vth* is affected by Vo. Owing to the time of interest [23], the response time would be observed decisively upon stress time. The wide range of response time from 10 ms to 10,000 s displays the evidence of widely distributing reaction rate for the Vo in the pool. Furthermore, the 100 times variation in ΔVth for the same response time also clearly demonstrates the diversity of vacancy pool. The result suggests the severe degradation caused by those faster Vo should be cautiously considered. Bedsides, the data out of the measurement limit cannot be included here, but it is believed that there are Vo in the pool can react to the light and bias at other different rates.

IV. CONCLUSION

A comprehensive vacancy pool model is proposed to provide an overall picture for V_O in a-IGZO TFT. The proposed model could universally explain the various degradation behavior under kinds of conditions, including those under light pulses with altering duty ratios. The wide distribution of reaction rate can make difficulty in using a-IGZO TFTs in applications that require stable characteristics under dynamic light ambiance. Therefore, the concept of "vacancy pool" should be kept in mind.

REFERENCES

[1] T. Kamiya, K. Nomura, and H. Hosono, "Present status of amorphous In–Ga–Zn–O thin-film transistors," *Sci. Technol. Adv. Mater.*, vol. 11, no. 4, pp. 44305–44327, Sep. 2010, doi: 10.1088/1468-6996/11/4/044305.

[2] S. Kim *et al.*, "The influence of visible light on the gate bias instability of In–Ga–Zn–O thin film transistors," *Solid-States Electron.*, vol. 62, no. 1, pp. 77–81, Aug. 2011, doi: 10.1016/j.sse.2011.04.014.

[3] C.-T. Lee *et al.*, "A novel highly transparent 6-in. AMOLED display consisting of IGZO TFTs," in *SID Dig. Tech. Papers*, pp. 872–875, Jun. 2015, pp. 872–875, doi: 10.1002/sdtp.10371.

[4] K. Nomura *et al.*, "Room-temperature fabrication of transparent flexible thin-film transistors using amorphous oxide semiconductors," *Nature*, vol. 432, pp. 488–492, Nov. 2004, doi: 10.1038/nature03090.

[5] H. Yamaguchi *et al.*, "11.7-inch flexible AMOLED display driven by a-IGZO TFTs on plastic substrate," in *SID Symp. Dig. Tech. Papers*, vol. 43, Jun. 2012, pp. 1002–1005, doi: 10.1002/j.2168-0159.2012.tb05961.x.

[6] H.-W. Zan *et al.*, "Amorphous indium-gallium-zinc-oxide visible-light phototransistor with a polymeric light absorption layer," *Appl. Phys. Lett.*, vol. 97, no. 20, pp. 1–3, Nov. 2010, doi: 10.1063/1.3517506.

[7] S. Jeon *et al.*, "180nm gate length amorphous InGaZnO thin film transistor for high density image sensor applications" in *Proc. IEEE IEDM*, Dec. 2010, pp. 21.3.1–21.3.4, doi: 10.1109/IEDM.2010.5703406.

[8] D. P. Gosain and T. Tanaka, "Instability of amorphous indium gallium zinc oxide thin film transistors under light illumination," *Jpn. J. Appl. Phys.*, vol. 48, no. 3, Mar. 2009, Art. no. 03B018, doi: 10.1143/JJAP.48.03B018.

[9] J. Li, L. Lu, R. Chen, H.-S. Kwok, and M. Wong, "A physical model for metal–oxide thin-film transistor under gate-bias and illumination stress," *IEEE Trans. Electron Devices*, vol. 65, no. 1, pp. 142–149, Jan. 2018, doi: 10.1109/TED.2017.2771800.

[10] K. Park *et al.*, "Reliability of crystalline indium–gallium–zinc–oxide thin-film transistors under bias stress with light illumination," *IEEE Trans. Electron Devices*, vol. 62, no. 9, pp. 2900–2905, Sep. 2019, doi: 10.1109/TED.2015.2458987.

[11] T.-Y. Hsieh *et al.*, "Investigating the drain-bias-induced degradation behavior under light illumination for InGaZnO thin-film transistors," *IEEE Electron Device Lett.*, vol. 33, no. 7, pp. 1000–1002, Jul. 2012, doi: 10.1109/LED.2012.2193112.

[12] X. Huang *et al.*, "Electrical instability of amorphous indium-gallium-zinc oxide thin film transistors under monochromatic light illumination," *Appl. Phys. Lett.*, vol. 100, no. 24, pp. 1–4, Jun. 2012, doi: 10.1063/1.4729478.

[13] J. Yao *et al.*, "Electrical and photosensitive characteristics of a-IGZO TFTs related to oxygen vacancy," *IEEE Trans. Electron Devices*, vol. 58, no. 4, pp. 1121–1126, Apr. 2011, doi: 10.1109/TED.2011.2105879.

[14] K. Takechi, M. Nakata, T. Eguchi, H. Yamaguchi, and S. Kaneko, "Comparison of ultraviolet photo-field effects between hydrogenated amorphous silicon and amorphous InGaZnO4 thin-film transistors," *Jpn. J. Appl. Phys.*, vol. 48, no. 1, Jan. 2009, Art. no. 010203, doi: 10.1143/JJAP.48.010203.

[15] H. Godo *et al.*, "Numerical analysis on temperature dependence of characteristics of amorphous In-Ga-Zn-Oxide TFT," in *SID Dig. Tech. Papers*, Jun. 2009, pp. 1110–1112, doi: 10.1889/1.3256479.

[16] C. Chen, K. Abe, H. Kumomi, and J. Kanicki, "Density of states of a-InGaZnO from temperature-dependent field-effect studies," *IEEE Trans. Electron Devices*, vol. 56, no. 6, pp. 1177–1183, Jun. 2009, doi: 10.1109/TED.2009.2019157.

[17] A. Suresh and J. F. Muth, "Bias stress stability of indium gallium zinc oxide channel based transparent thin film transistors," *Appl. Phys. Lett.*, vol. 92, no. 3, Jan. 2008, Art. no. 033502, doi: 10.1063/1.2824758.

[18] M. E. Lopes *et al.*, "Gate-bias stress in amorphous oxide semiconductors thin-film transistors," *Appl. Phys. Lett.*, vol. 95, no. 6, Aug. 2009, Art. no. 063502, doi: 10.1063/1.3187532.

[19] E. N. Cho, J. H. Kang, C. E. Kim, P. Moon, and I. Yun, "Analysis of bias stress instability in amorphous InGaZnO thin-film transistors," *IEEE Trans. Device Mater. Rel.*, vol. 11, no. 1, pp. 112–117, Mar. 2011, doi: 10.1109/TDMR.2010.2096508.

[20] Y.-H. Tai, C.-Y. Chang, Y.-W. Chen, and Y.-J. Chen, "The time response of the on-current for the amorphous In-Ga-Zn-O thin film transistor to the illumination pulse," *ECS J. Solid-State Sci. Technol.*, vol. 3, no. 9, pp. Q3071–Q3075, Aug. 2014, doi: 10.1149/2.012409jss.

[21] Y.-H. Tai, C.-Y. Chang, and Y.-W. Chen, "The current behaviors of the amorphous In-Ga-Zn-O thin-film transistor under varying illumination conditions," *J. Display Technol.*, vol. 12, no. 4, pp. 351–356, Apr. 2016, doi: 10.1109/JDT.2015.2488291.

[22] Y.-H. Tai, C.-Y. Chang, P.-C. Chan, and J.-J. Dai, "Drain current response to fast illumination pulse for amorphous In–Ga–Zn–O thin-film transistor," *IEEE Trans. Electron Devices*, vol. 63, no. 12, pp. 4782–4787, Dec. 2016, doi: 10.1109/TED.2016.2615883.

[23] H.-W. Liu, P.-C. Chan, J.-H. Lin, C.-Y. Chang, and Y.-H. Tai, "Analysis of the short-term response in the drain current of a-IGZO TFT to light pulses," *IEEE Electron Device Lett.*, vol. 38, no. 7, pp. 887–889, Jul. 2017, doi: 10.1109/LED.2017.2705701.

[24] Y.-H. Tai, H.-L. Chiu, and L.-S. Chou, "The deterioration of a-IGZO TFTs owing to the copper diffusion after the process of the source/drain metal formation," *J. Electrochem. Soc.*, vol. 159, no. 5, pp. 200–203, Mar. 2012, doi: 10.1149/2.025206jes.

[25] T.-C. Chen *et al.*, "Analyzing the effects of ambient dependence for InGaZnO TFTs under illuminated bias stress," *Surface Coatings Technol.*, vol. 231, pp. 465–470, Sep. 2013, doi: 10.1016/j.surfcoat.2011.12.048.

[26] V. Gradisnik, M. Pavlovic, B. Pivac, and I. Zulim, "Transient response times of a-Si : H p-i-n color detector," *IEEE Trans. Electron Devices*, vol. 53, no. 10, pp. 2485–2491, Oct. 2006, doi: 10.1109/TED.2006.882265.

[27] N. V. Joshi, "Analytical approach towards transient phenomena in photoconductors," *Phys. Rev. B, Condens. Matter*, vol. 27, no. 10, pp. 6272–6278, May 1983, doi: 10.1103/PhysRevB.27.6272.

[28] K. Winer, "Chemical-equilibrium description of the gap-state distribution in a-Si:H," *Phys. Rev. Lett.*, vol. 63, no. 14, pp. 1487–1490, Oct. 1989, doi: 10.1103/PhysRevLett.63.1487.

[29] M. J. Powell, C. van Berkel, A. R. Franklin, S. C. Deane, and W. I. Milne, "Defect pool in amorphous-silicon thin-film transistors," *Phys. Rev. B, Condens. Matter,* vol. 45, pp. 4160–4170, Feb. 1992, doi: 10.1103/PhysRevB.45.4160.

[30] M. J. Powell and S. C. Deane, "Improved defect-pool model for charged defects in amorphous silicon," *Phys. Rev. B, Condens. Matter*, vol. 48, pp. 10815–10827, Oct. 1993, doi: 10.1103/PhysRevB.48.10815.

[31] Y.-H. Tai, H.-W. Liu, P.-C. Chan, and S.-L. Chiu, "Degradation of a-IGZO thin-film transistors under negative bias and illumination stress in the time span of a few seconds," *IEEE Electron Device Lett.*, vol. 39, no. 5, pp. 696–698, May 2018, doi: 10.1109/LED.2018.2821170.

[32] S. K. Lee *et al.*, "Comparative study of electrical instabilities in InGaZnO thin film transistors with gate dielectrics," *Microelectron. Rel.*, vol. 52, nos. 9–10, pp. 2504–2507, Sep./Oct. 2012, doi: 10.1016/j.microrel.2012.06.134.

[33] T.-C. Chen, Y. Kuo, T.-C. Chang, M.-C. Chen, and H.-M. Chen, "Mechanism of a-IGZO TFT device deterioration—Illumination light wavelength and substrate temperature effects," *J. Phys. D Appl. Phys.*, vol. 50, no. 42, Aug. 2017, Art. no. 42LT02, doi: 10.1088/1361-6463/aa864c.

[34] M. Wang, J. Xu, H. Wang, and Q. Shan, "A unified model to understand degradation of a-InGaZnO TFTs under various gate bias stresses with or without light illumination," in *Proc. Int. Symp. Phys. Failure Anal. Integr. Circuits (IPFA)*, 2015, pp. 76–79, doi: 10.1109/IPFA.2015.7224337.

[35] W.-T. Chen, H.-W. Hsueh, H.-W. Zan, and C.-C. Tsai, "Light-enhanced bias stress effect on amorphous In-Ga-Zn-O thin-film transistor with lights of varying colors," *Electrochem. Solid-State Lett.*, vol. 14, no. 7, pp. H297–H299, May 2011, doi: 10.1149/1.3584088.
[36] J.-S. Kim *et al.*, "A light-induced threshold voltage instability based on a negative-u center in a-IGZO TFTs with different oxygen flow rates," *Trans. Electr. Electron. Mater.*, vol. 15, no. 6, pp. 315–319, Dec. 2014, doi: 10.4313/TEEM.2014.15.6.315.
[37] D. Shin, E. N. Cho, S. Park, and I. Yun, "Effect of SiOx/SiNx stacked gate dielectric structure on the instability of a-IGZO thin film transistors," *ECS Trans.*, vol. 60, no. 1, pp. 951–955, Mar. 2014, doi: 10.1149/06001.0951ecst.

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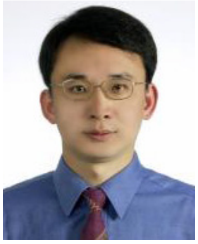

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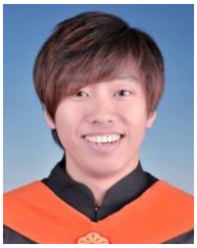

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