IEEE Access
Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

Received July 13, 2019, accepted August 4, 2019, date of publication August 20, 2019, date of current version August 31, 2019.

Digital Object Identifier 10.1109/ACCESS.2019.2936405

Long-Term Behavior of Hydrogenated Amorphous Silicon Thin-Film Transistors Covered With Color Filters for Use in Optical Sensors

FU-HSING CHEN[1], CHIA-LUN LEE[1], JUI-HUNG CHANG[1], WEI-SHENG LIAO[1], CHIEH-AN LIN[1], CHIA-WEI KUO[2], AND CHIH-LUNG LIN[1,3], (Member, IEEE)
[1]Department of Electrical Engineering, National Cheng Kung University, Tainan 701-01, Taiwan
[2]AU Optronics Corporation, Hsinchu 300-78, Taiwan
[3]Advanced Optoelectronic Technology Center, National Cheng Kung University, Tainan 701-01, Taiwan

Corresponding author: Chih-Lung Lin (cllin@ee.ncku.edu.tw)

This work was supported in part by the Advanced Optoelectronic Technology Center, National Cheng Kung University, Tainan, Taiwan, in part by the Ministry of Science and Technology of Taiwan under Project MOST 107-2221-E-006-184-MY3 and Project MOST 107-2218-E-006-003, and in part by the AU Optronics Corporation.

ABSTRACT This work investigates the long-term behavior of photo thin-film transistors (TFTs) that are covered with color filters and based on hydrogenated amorphous silicon (a-Si:H) technology. Based on the electrical characteristics and the optical responses of these TFTs as measured under different stress conditions, a new method for driving a photo TFT with a negative gate-source voltage is proposed to suppress the degradation of the photocurrent. The effectiveness of the newly proposed method is verified using our previously developed white-light photocurrent gating (WPCG) structure, the measurement of photocurrents, and the established models of red, green, and blue photo TFTs. An accelerated lifetime test of the fabricated circuit was carried out at 70 °C and under the illumination of ambient light for 504 hours, demonstrating that the proposed method improves the long-term reliability of optical sensors.

INDEX TERMS Hydrogenated amorphous silicon thin-film transistor, long-term reliability, optical sensor.

I. INTRODUCTION

Hydrogenated amorphous silicon thin-film transistors (a-Si:H TFTs) are extensively used in switching devices and peripheral driver circuits for active-matrix liquid crystal displays (AMLCDs) owing to their low cost, high uniformity over a large-area substrate, and the maturity of their fabrication process [1]–[8]. The higher photo-sensitivity of a-Si:H TFTs under illumination by visible light in comparison to amorphous-indium-gallium-zinc-oxide (a-IGZO) favors their use in optical sensors in displays, supporting X-ray image sensing, backlighting, and optical input functions [1], [3], [9], [10]. Moreover, the integration of TFT-based optical sensors into a large interactive panel can easily realize multipoint optical inputs, such as those generated using a light emitting diode (LED) pen, without the need for a complex algorithm or an additional sensing module [3]. Therefore, many optical sensor circuits for transforming the intensity of optical inputs into electrical signals have been proposed [3], [11]–[17]. Abileah *et al.* [11] proposed a conventional optical sensor circuit with a simple structure composed of only one photo TFT to sense the intensity of the optical input signal, one storage capacitor, and one readout TFT to sample the sensing result. Ideally, the optical sensor can generate a substantial difference in sensing results, enabling its illumination by an optical input signal in order to be easily detected. However, intense ambient white light may yield an abnormal sensing result owing to a large induced photocurrent in the photo TFT. Thus, some works, based on our previously developed white-light photocurrent gating (WPCG) structure, have sought to prevent false detection due to the illumination by ambient light [13]–[17]. The WPCG structure adopts three photo TFTs with red, green, and blue color filters, respectively. One photo TFT is the main sensing device that detects the optical input signal. The other two photo TFTs generate compensating photocurrents based

The associate editor coordinating the review of this article and approving it for publication was Yue Zhang.

on the sensed intensities of light of a corresponding color to maintain the high sensitivity of the WPCG structure under intense ambient light. However, the degradation of photocurrents that is generated by a-Si:H TFTs under illumination and long-term operation is not negligible. To suppress the degradation of a-Si:H photo TFTs, an optical sensor that uses two sets of sensing structures to reduce the duration of the stress of a photo TFT was proposed [17]. Even though the reliability of the optical sensor is improved, the two structures for the alternating operation are too complex to use with a high sensor density.

This work investigates the electrical characteristics of a-Si:H TFTs that are covered with conventional color filters used in an LCD process at high temperature under different stress conditions. Based on the measured photocurrents of the a-Si:H TFTs under illumination by ambient light of 4,000 lux at 70 °C for 72 hours, a new method for ameliorating the degradation of photo TFTs using a negative applied gate-source voltage, without increasing the number of components in the optical sensor circuit, is proposed. The feasibility of this proposed method is evaluated by measuring the photocurrents of the red, green, and blue photo TFTs, and using established models for HSPICE simulation. Experimental results demonstrate that the fabricated optical sensor circuit that is driven using the proposed method retains high sensitivity under ambient light of 10,000 lux during a 504 h-long accelerated lifetime test at 70 °C. Therefore, this design favors the reliability of an optical sensor circuit under long-term high-temperature stress in ambient light.

II. DEVICE CHARACTERISTICS

The photo a-Si:H TFTs in this work are fabricated on glass substrates using the standard a-Si:H TFT process and have a bottom gate structure. The black matrix of each TFT is removed to improve its photo sensitivity. To allow the input light of a particular color to enter the channel area, each photo TFT is covered with a red, green, or blue filter [13]–[17]. Under illumination, several electron-hole pairs are generated in the amorphous silicon film, so the separation of electron-hole pairs and the redistribution of space charge result in the generation of a significant photocurrent [18], [19]. Fig. 1 presents the measured transfer characteristics (drain current versus gate-source voltage) of a blue photo TFT, obtained using a Keithley 2612A source meter. The channel width and the channel length of the photo TFTs are 60 μm and 8 μm, respectively. The drain currents are measured at a drain-source voltage of 10 V in the dark, under illumination by a white LED at 4,000 lux, and illumination by a white LED at 4,000 lux together with a blue LED at 2,500 lux. Notably, the commercialized white LED combines a blue LED and a yellow phosphor, so the emitting light includes a blue light (~450 nm) and a yellow light (~560 nm). The peak wavelength of the blue LED that is used in this work is 470 nm. The optical transmission rates of color filters under illumination by the light with various wavelengths was investigated in our previous work [16].

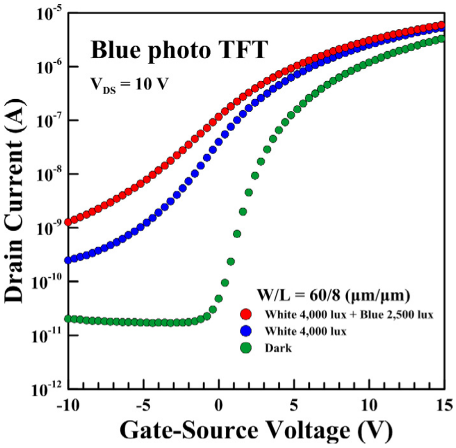


FIGURE 1. Measured transfer characteristics of blue photo TFT.

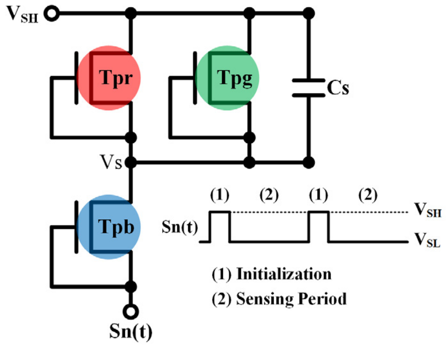


FIGURE 2. Our previously developed WPCG structure for detecting blue optical input signal along with corresponding timing diagram.

Fig. 2 shows our previously developed WPCG structure for detecting a blue optical input signal along with the corresponding timing diagram. Tpb is a blue photo TFT for sensing the intensity of the optical input signal. Tpr and Tpg—red and green photo TFTs, respectively—are used to prevent ambient light from influencing the charges that are stored in the capacitor, Cs. The operation theory of the WPCG structure during the sensing period can be illustrated with reference to the optical characteristics of red, green, and blue photo TFTs. Fig. 3 plots the measured photocurrents (drain current versus drain-source voltage) under illumination by ambient white light at 4,000 lux. The drain-source voltage is set from 0 V to 25 V, and the drain currents are measured at a gate-source voltage of 0 V. Under only ambient white light, the sum of I_{Tpr} and I_{Tpg}, which are generated by the red and green photo TFTs, should be larger than I_{Tpb}, the photocurrent of a blue photo TFT, owing to the designed favorable aspect ratios of the photo TFTs. By Kirchhoff's current law, the current that flows into node Vs of the WPCG structure ($I_{Tpr} + I_{Tpg}$) equals that which flows out of node Vs (I_{Tpb}). Therefore, the voltage of the Vs node can be obtained when the drain-source voltage of Tpr and Tpg plus that of Tpb equals V_{SH} minus the low voltage of the Sn(t) signal, which is 25 V in this work. The drain-source voltage of Tpr and Tpg is 2.4 V, and that

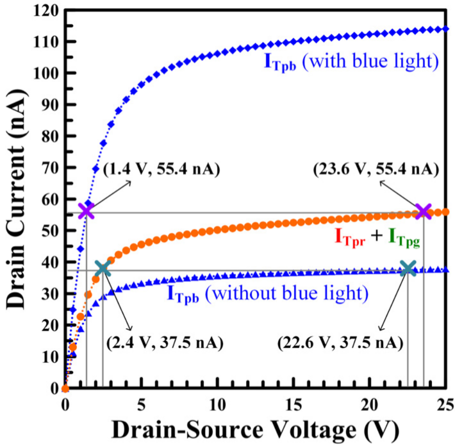


FIGURE 3. Measured photocurrents at gate-source voltage of 0 V under illumination by ambient white light at 4,000 lux.

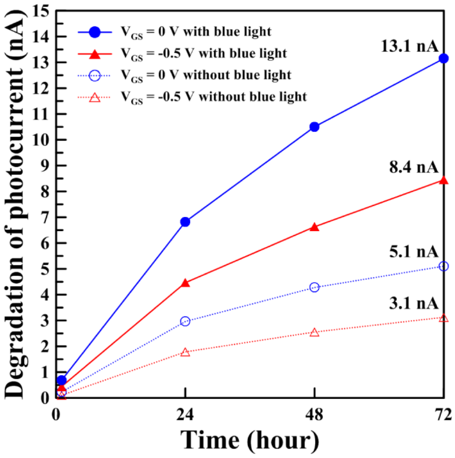
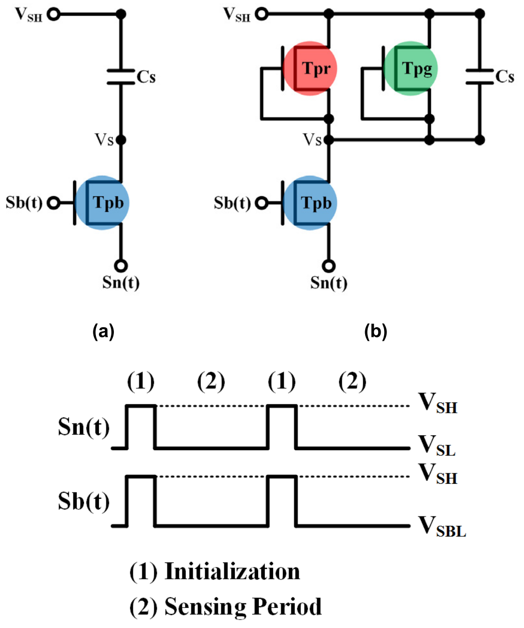


FIGURE 4. Changes in photocurrent that occur when blue photo TFTs are driven using different gate-source voltages under long-term stress by illumination.

of Tpb is 22.6 V. In contrast, when the blue light input signal is applied, I_{Tpb}, which is generated by the blue photo TFT, increases significantly and becomes larger than the sum of I_{Tpr} and I_{Tpg}. In this case, the drain-source voltage of Tpr and Tpg is increased to 23.6 V, and that of Tpb is decreased to 1.4 V. Thus, the change in I_{Tpb} produces a large change in the voltage at node Vs, so whether or not a blue light input signal has been applied can be determined.

Based on the operation that is described above, when no blue optical input signal is applied, the drain-source voltage of the blue photo TFT is much larger than that of the red and green photo TFTs, significantly degrading the blue photo TFT in the WPCG structure. Moreover, when the blue optical signal illuminates the WPCG structure, the degradation of the photocurrent increases the settling time for the voltage at node Vs to reach the balanced situation of $I_{Tpb} = I_{Tpr} + I_{Tpg}$. Therefore, suppressing the degradation of the blue photo TFT is important to avoid malfunctions of the WPCG structure. Generally, the degradation of a-Si:H TFTs is related to the gate-source voltage during long-term operation [20], so Fig. 4 plots the changes in the photocurrent that occur when the blue photo TFTs are driven using different gate-source voltages under long-term stress by illumination. The measurements are made under illumination with ambient light of 4,000 lux at 70 °C for 72 hours. The drain-source voltage is set to 25 V as a stress condition to meet the operation during the sensing period when no optical input signal is applied. As shown in Fig. 4, when the applied gate-source voltage is 0 V, the photocurrents of the blue photo TFT with and without illumination by the blue light of 2,500 lux are degraded by 13.1 nA and 5.1 nA, respectively, even though the TFT is driven under no gate-source stress. In contrast, as the gate-source voltage is adjusted from 0 V to −0.5 V, the drain currents of the blue photo TFTs are degraded by only 8.4 nA and 3.1 nA, respectively. Accordingly, the photo TFT driven using a negative gate-source voltage degrades less than one driven without gate-source stress, and is suitable for use in a highly reliable optical sensor.



(a)

(b)

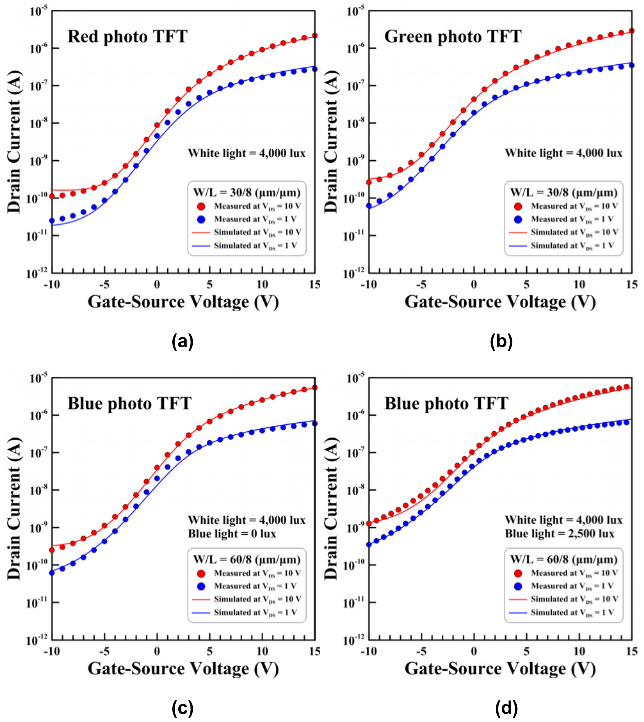
(c)

FIGURE 5. (a) Conventional optical sensor circuit and (b) modified WPCG structure along with (c) corresponding timing diagram when newly proposed method is used.

III. RESULTS AND DISCUSSION

Fig. 5 presents the conventional optical sensor circuit and the modified WPCG structure along with the corresponding timing diagram when the newly proposed method is used. Notably, signal Sb(t) has the same timing design as signal Sn(t), but a different low voltage level to maintain the negative gate-source voltage of Tpb during the sensing period, suppressing the degradation of the photocurrent.

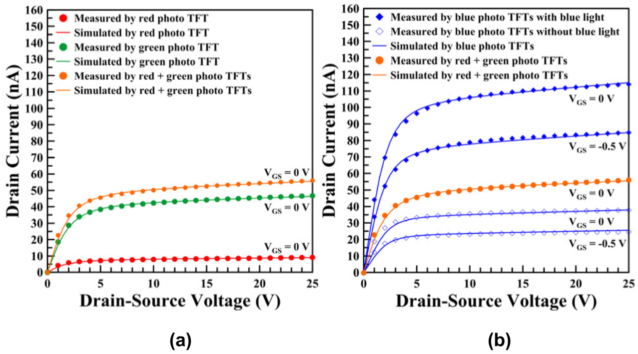
To verify the feasibility of the newly proposed method for driving the optical sensors, HSPICE simulation is performed based on established TFT models (Rensselaer Polytechnic



(a) (b)

(c) (d)

FIGURE 6. Measured and simulated transfer curves of a-Si:H photo TFTs under illumination by white light of 4,000 lux with drain-source voltages of 1 V and 10 V.



(a) (b)

FIGURE 7. Measured and simulated photocurrents. (a) Red and green photo TFTs with gate-source voltage of 0 V. (b) Blue photo TFT with gate-source voltages of 0 V and −0.5 V.

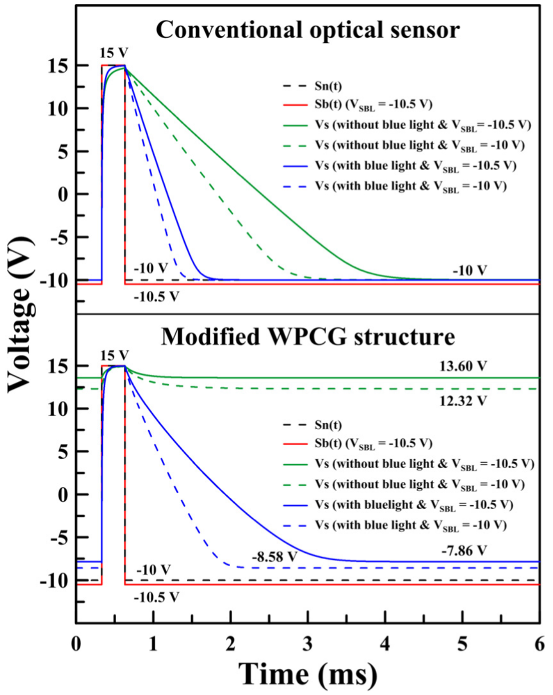
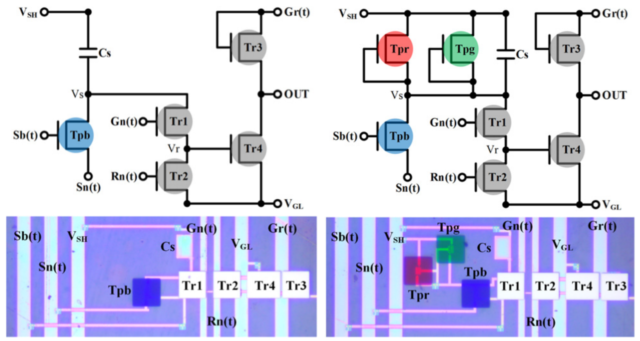


FIGURE 8. Simulated waveforms of Sn(t), Sb(t), and those at Vs nodes of conventional optical sensor circuit and modified WPCG structure.

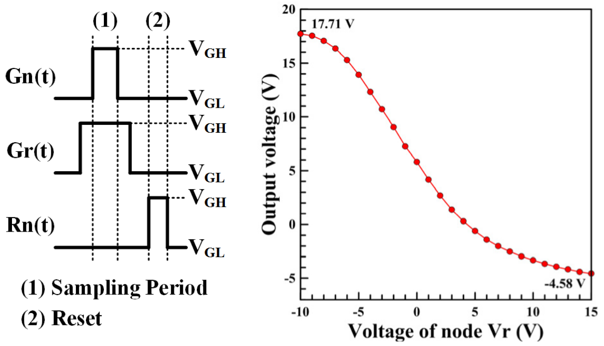
Institute a-Si TFT model, level = 61). Fig. 6 plots the measured and simulated transfer curves of a-Si:H photo TFTs under the illumination by white light of 4,000 lux with drain-source voltages of 1 V and 10 V. Figs. 6(a) and 6(b) are obtained using red and green photo TFTs with an aspect ratio of 30 μm/ 8 μm. Figs. 6(c) and 6(d) are obtained using a blue photo TFT with an aspect ratio of 60 μm/ 8 μm, without and with the blue illumination of 2,500 lux. Fig. 7 plots the measured and simulated photocurrents of the red and green photo TFTs with a gate-source voltage of 0 V and those of a blue photo TFT with the gate-source voltages of 0 V and −0.5 V. Even though the photocurrents that are measured at a gate-source voltage of −0.5 V are smaller than those measured at a gate-source voltage of 0 V, based on the operation of the WPCG structure, the drain-source voltage of Tpb can still be predicted to be 2.2 V and 23.7 V with and without the blue optical input signal, respectively.

Fig. 8 plots the simulated waveforms of Sn(t), Sb(t), and those at the Vs nodes of the conventional optical sensor circuit and the modified WPCG structure. Sn(t) ranges from −10 V to 15 V; the high voltage of Sb(t) equals that of Sn(t) while the low voltage of Sb(t) is set to −10 V and −10.5 V. The capacitance of Cs in both sensors is set to 3 pF that is much larger than the parasitic capacitance of the photo TFTs, as the value of the oxide capacitance per unit area (Cox) of the photo TFTs in this work is about 0.15 fF/μm^2. When Sn(t) and Sb(t) are at 15 V, each Vs node is reset to a high voltage, which is about 15 V. In the sensing period, the gate-source voltage of Tpb is 0 V when the low voltage of Sb(t) is −10 V, and the gate-source voltage of Tpb is −0.5 V when the low voltage of Sb(t) is −10.5 V. As shown in Fig. 8, the Vs node of the conventional optical sensor circuit is discharged to −10 V during the sensing period, regardless of whether the blue optical input signal is applied. In contrast, the Vs node in the modified WPCG structure is maintained at 12.32 V when Tpb is driven with a gate-source voltage of 0 V and only white light is applied. When the gate-source voltage of Tpb is adjusted from 0 V to −0.5 V, the voltage at Vs changes from 12.32 V to 13.60 V because a smaller photocurrent is generated by Tpb. Herein, the drain-source voltage of Tpb is increased from 22.32 V to 23.60 V. However, when a blue optical input signal illuminates the modified WPCG structure, Tpb, which is driven with the gate-source voltages



(a) (b)

FIGURE 9. Circuit diagrams and optical images of fabricated circuits. (a) Conventional optical sensor circuit. (b) Modified WPCG structure.



(a) (b)

FIGURE 10. (a) Timing diagram and (b) measured transfer curve of readout circuit.

TABLE 1. Designed parameters and voltage levels in experiment.

Parameter	Value
$(W/L)_{Tpb}$	80/8 (μm/μm)
$(W/L)_{Tpr、Tpg}$	40/8 (μm/μm)
$(W/L)_{Tr1、Tr2、Tr3}$	60/6 (μm/μm)
$(W/L)_{Tr4}$	360/6 (μm/μm)
Cs	3 pF
Sn(t)	-10 V ~ 15 V
Sb(t)	-10.5 V ~ 15 V
Gn(t)、Gr(t)、Rn(t)	-10 V ~ 25 V
V_{SH}	15 V
V_{GL}	-10 V

of 0 V and −0.5 V, can generate significant photocurrents that counteract those generated by Tpr and Tpg, discharging the Vs node to −8.58 V and −7.86 V, respectively. Herein, the drain-source voltages of Tpb are 1.42 V and 2.14 V. Based on the aforementioned results, the newly proposed method can still generate a 21.46 V voltage difference at the Vs node, enabling a blue light input signal without ambient light to be detected, consistent with the theory of the operation of our WPCG structure.

To evaluate the performance of the proposed driving method, a conventional optical sensor circuit and a modified WPCG structure were fabricated with an inverter-type readout circuit. Fig. 9 shows the circuit diagrams and the optical images of the fabricated circuits. Notably, the TFTs in the readout circuit (Tr1-Tr4) are covered with a metal layer to shield them from light. Table 1 presents the designed parameters and the voltage levels in the experiment. Fig. 10 presents the timing diagram and plots the measured transfer curve of the readout circuit. The output voltage ranges from 17.71 V to −4.58 V as the voltage that is applied to the V_r node is increased from −10 V to 15 V; as such, this readout circuit is used for sampling sensing results from charges that are stored in the capacitors in both the conventional optical sensor and the WPCG structure. Fig. 11 plots the measured waveforms of Gn(t) during the sampling period and compares the output voltages of the fabricated circuits under ambient white light with intensities of 1,000 lux and 4,000 lux. As shown in Fig. 11(a), both the conventional

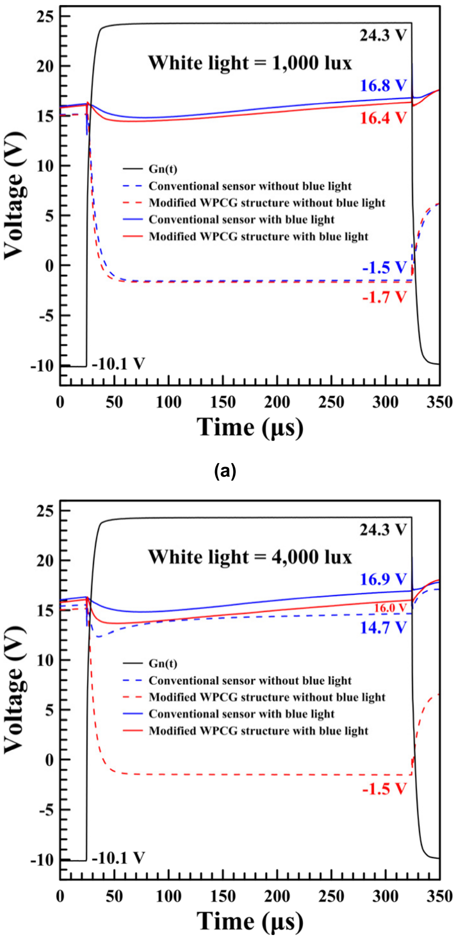


FIGURE 11. Measured waveforms of Gn(t) during sampling period and output voltages of fabricated circuits under ambient white light. (a) With intensity of 1,000 lux. (b) With intensity of 4,000 lux.

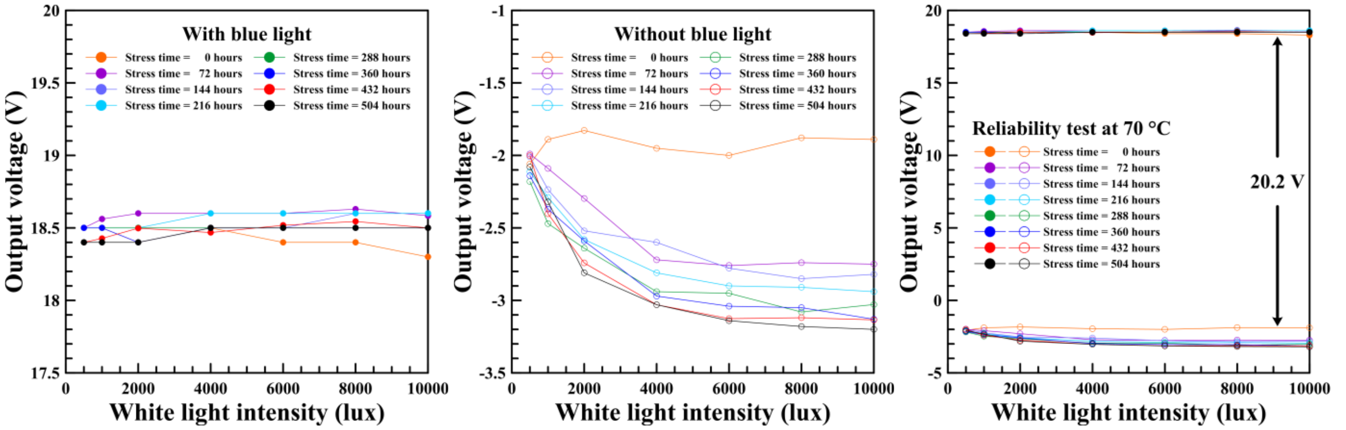


FIGURE 12. Measured output voltages of modified WPCG structure under ambient light intensities from 500 lux to 10,000 lux during 504 h of operation.

optical sensor and the modified WPCG structure can generate large differences in the output voltages of 18.3 V and 18.1 V, respectively, enabling a blue light input signal of 2,500 lux to be distinguished from illumination by a weak ambient white of 1,000 lux. However, when the intensity of the ambient white light is increased to 4,000 lux, the difference in the output voltages of the conventional optical sensor significantly decreases from 18.3 V to 2.2 V, due to the fact that the output voltage is 14.7 V even when no blue light input signal is applied, as shown in Fig. 11(b). In contrast, the output voltages of the modified WPCG structure with and without the illumination of blue light are 16.0 V and −1.5 V, respectively, yielding a voltage difference of 17.5 V. The reliability of the modified WPCG structure that uses the newly proposed method is investigated by performing an accelerated lifetime test at 70 °C under the illumination by ambient light of 4,000 lux. Fig. 12 plots the measured output voltages of the modified WPCG structure under ambient light intensities from 500 lux to 10,000 lux during 504 h of operation. Since the proposed method uses a negative gate-source voltage to suppress the degradation of the blue photo TFT, the output voltages with and without a blue optical input signal are almost identical. The significant differences in output voltages, which exceed 20 V throughout the reliability test, confirm the immunity against malfunctions of the WPCG structure caused by ambient light. Thus, the proposed method is practically feasible.

IV. CONCLUSION

The long-term behavior of photo a-Si:H TFTs under illumination with different gate-source voltages was investigated in this work. Measurements made on the fabricated photo TFTs revealed that the degradation of photocurrent could be suppressed by adjusting the gate-source voltage from 0 V to −0.5 V. Thus, a new method for driving the photo TFT using a negative gate-source voltage was proposed and its effectiveness was verified using both established models for HSPICE simulation and fabricated samples for measurement. The experimental results demonstrate that the modified WPCG structure that uses the newly proposed method exhibits immunity against the effects of the ambient illumination of up to 10,000 lux throughout a long-term operation for 504 hours. Accordingly, the proposed driving method enhances the reliability and improves the lifetime of applications with optical input functions that involve the a-Si:H process.

ACKNOWLEDGMENT

The author would like to thank AU Optronics Corporation for its technical support.

REFERENCES

[1] S. M. Gadelrab and S. G. Chamberlain, "The source-gated amorphous silicon photo-transistor," *IEEE Trans. Electron Devices*, vol. 44, no. 10, pp. 1789–1794, Oct. 1997. doi: 10.1109/16.628838.

[2] Y. Chen, J. Au, P. Kazlas, A. Ritenour, H. Gates, and J. Goodman, "Ultrathin, high-resolution, flexible electronic ink displays addressed by a-Si active-matrix TFT backplanes on stainless steel foil," in *IEDM Tech. Dig.*, Dec. 2002, pp. 389–392. doi: 10.1109/IEDM.2002.1175860.

[3] C. J. Brown, H. Kato, K. Maeda, and B. Hadwen, "A continuous-grain silicon-system LCD with optical input function," *IEEE J. Solid-State Circuits*, vol. 42, no. 12, pp. 2904–2912, Dec. 2007. doi: 10.1109/JSSC.2007.908695.

[4] J. Chen and C. T. Liu, "Technology advances in flexible displays and substrates," *IEEE Access*, vol. 1, pp. 150–158, 2013. doi: 10.1109/ACCESS.2013.2260792.

[5] C.-L. Lin, M.-H. Cheng, C.-D. Tu, C.-C. Hung, and J.-Y. Li, "2-D–3-D switchable gate driver circuit for TFT-LCD applications," *IEEE Trans. Electron Devices*, vol. 61, no. 6, pp. 2098–2105, Jun. 2014. doi: 10.1109/TED.2014.2319096.

[6] C.-L. Lin, F.-H. Chen, M.-X. Wang, P.-C. Lai, and C.-H. Tseng, "Gate driver based on a-Si:H thin-film transistors with two-step-bootstrapping structure for high-resolution and high-frame-rate displays," *IEEE Trans. Electron Devices*, vol. 64, no. 8, pp. 3494–3497, Aug. 2017. doi: 10.1109/TED.2017.2710180.

[7] T. M. Fernández-Caramés and P. Fraga-Lamas, "A review on human-centered IoT-connected smart labels for the industry 4.0," *IEEE Access*, vol. 6, pp. 25939–25957, 2018. doi: 10.1109/ACCESS.2018.2833501.

[8] B. Hekmatshoar, "Electrical stability and flicker noise of thin-film heterojunction FETs on poly-Si substrates," *IEEE Access*, vol. 7, pp. 77063–77069, 2019. doi: 10.1109/ACCESS.2019.2921233.

[9] Y. H. Tai, L. S. Chou, Y. F. Kuo, and S. W. Yen, "Gap-type a-Si TFTs for backlight sensing application," *J. Display Technol.*, vol. 7, no. 8, pp. 420–425, Aug. 2011. doi: 10.1109/JDT.2011.2135838.

[10] H. Ou, K. Wang, J. Chen, A. Nathan, S. Z. Deng, and N. S. Xu, "Dual-gate photosensitive FIN-TFT with high photoconductive gain and near-UV to near-IR responsivity," in *IEDM Tech. Dig.*, Dec. 2016, pp. 32.5.1–32.5.4. doi: 10.1109/IEDM.2016.7838529.

[11] A. Abileah, W. den Boer, T. Larsson, T. Baker, S. Robinson, R. Siegel, N. Fickenscher, B. Leback, T. Griffin, and P. Green, "59.3: Integrated optical touch panel in a 14.1' AMLCD," in *SID Symp. Dig. Tech. Papers*, vol. 35, no. 1, pp. 1544–1547, May 2004. doi: 10.1889/1.1821371.

[12] W. den Boer, T. Nguyen, and P. J. Green, "Image sensor with photosensitive thin film transistors and dark current compensation," U.S. Patent 8 289 429 B2, Oct. 16, 2012.

[13] C.-L. Lin, C.-E. Wu, P.-S. Chen, P.-C. Lai, J.-S. Yu, C. Chang, and Y.-H Tseng, "Optical pixel sensor of hydrogenated amorphous silicon thin-film transistor free of variations in ambient illumination," *IEEE J. Solid-State Circuits*, vol. 51, no. 11, pp. 2777–2785, Nov. 2016. doi: 10.1109/JSSC.2016.2599519.

[14] C.-L. Lin, C.-E. Wu, P.-S. Chen, C.-H. Chang, C.-C. Hsu, J.-S. Yu, C. Chang, and Y.-H. Tseng, "Hydrogenated amorphous silicon thin-film transistor-based optical pixel sensor with high sensitivity under ambient illumination," *IEEE Electron Device Lett.*, vol. 37, no. 11, pp. 1446–1449, Nov. 2016. doi: 10.1109/LED.2016.2607235.

[15] C.-L. Lin, P.-S. Chen, C.-H. Chang, J.-S. Yu, C. Chang, and Y.-H. Tseng, "A hydrogenated amorphous silicon thin-film transistor optical pixel sensor for ameliorating influences of ambient light and reflected light," *IEEE J. Electron Devices Soc.*, vol. 5, no. 4, pp. 262–265, Jul. 2017. doi: 10.1109/JEDS.2017.2695491.

[16] C.-L. Lin, C.-E. Wu, W.-C. Chiu, W.-L. Wu, and J.-S. Yu, "Optical properties of hydrogenated amorphous silicon thin-film transistor-based optical pixel sensor in three primary colors," *IEEE J. Sel. Topics Quantum Electron.*, vol. 24, no. 2, Mar./Apr. 2018, Art. no. 6000108. doi: 10.1109/JSTQE.2017.2701554.

[17] C.-L. Lin, C.-E. Wu, C.-L. Lee, F.-H. Chen, Y.-S. Lin, W.-L. Wu, and J.-S. Yu, "Alternately controlled optical pixel sensor system using amorphous silicon thin-film transistors," *IEEE Trans. Ind. Electron.*, vol. 66, no. 9, pp. 7366–7375, Sep. 2019. doi: 10.1109/TIE.2018.2880718.

[18] C. van Berkel and M. J. Powell, "The photosensitivity of amorphous silicon thin film transistors," *J. Non-Crystalline Solids*, vols. 77–78, pp. 1393–1396, Dec. 1985. doi: 10.1016/0022-3093(85)90915-9.

[19] M. J. Powell, "The physics of amorphous-silicon thin-film transistors," *IEEE Trans. Electron Devices*, vol. 36, no. 12, pp. 2753–2763, Dec. 1989. doi: 10.1109/16.40933.

[20] D. Zhou, M. Wang, and S. Zhang, "Degradation of amorphous silicon thin film transistors under negative gate bias stress," *IEEE Trans. Electron Devices*, vol. 58, no. 10, pp. 3422–3427, Oct. 2011. doi: 10.1109/TED.2011.2161635.

FU-HSING CHEN received the B.S. and M.S. degrees in electrical engineering from National Cheng Kung University, Tainan, Taiwan, in 2013 and 2015, respectively, where he is currently pursuing the Ph.D. degree in electrical engineering. His research interests include the optical sensor and the gate driver circuit design on glass for AMLCD and the pixel circuit design for AMOLED.

CHIA-LUN LEE received the B.S. and M.S. degrees in electrical engineering from National Cheng Kung University, Tainan, Taiwan, in 2016 and 2018, respectively, where he is currently pursuing the Ph.D. degree in electrical engineering. His current research interests include gate driver circuit design for AMLCD, pixel circuit design for AMOLED, and optical pixel sensor circuit design.

JUI-HUNG CHANG received the B.S. degree in electrical engineering from National Central University, Taoyuan, Taiwan, in 2017. He is currently pursuing the M.S. degree in electrical engineering with National Cheng Kung University, Tainan, Taiwan. His research interests include the gate driver circuit design on glass for AMLCD and the pixel circuit design for AMOLED.

WEI-SHENG LIAO received the B.S. degree in electrical engineering from National Cheng Kung University, Tainan, Taiwan, in 2018, where he is currently pursuing the M.S. degree in electrical engineering. His research interest includes the system circuit design for AMOLED and AMLCD displays.

CHIEH-AN LIN received the B.S. degree in electronic engineering from the National Kaohsiung University of Science and Technology, Kaohsiung, Taiwan, in 2018. He is currently pursuing the M.S. degree in electrical engineering with National Cheng Kung University, Tainan, Taiwan. His research interest includes the system circuit design for AMOLED and AMLCD displays.

CHIA-WEI KUO received the B.S. and Ph.D. degrees from the Department of Physics, National Cheng Kung University, Tainan, Taiwan, in 2001 and 2006, respectively. In 2006, he joined the Industrial Technology Research Institute (ITRI), Hsinchu, Taiwan, for the development of flexible LCD project. In 2011, he joined AU Optronics Corporation (AUO) as the Manager of the Advanced Display Optical Research Department. He has been mainly working on pixel circuit design and architectures for advanced displays.

CHIH-LUNG LIN (M'07) received the M.S. and Ph.D. degrees in electrical engineering from National Taiwan University, Taiwan, in 1993 and 1999, respectively. He is currently a Professor with the Department of Electrical and Engineering, National Cheng Kung University, Tainan, Taiwan. His current research interests include pixel circuit design for AMOLED and BPLCD, gate driver circuit design for AMLCD, and flexible display circuits.