Received 8 February 2022; revised 24 March 2022; accepted 26 March 2022. Date of publication 1 April 2022; date of current version 11 April 2022.
The review of this article was arranged by Editor M. K. Radhakrishnan.

Digital Object Identifier 10.1109/JEDS.2022.3164082

The Noise Behavior of Gap-Type Amorphous Silicon TFT Under Illumination

YA-HSIANG TAI (Senior Member, IEEE), YI-CHENG YUAN, CHENG-CHE TU, AND PIN-CHUN WANG

Department of Photonics and Institute of Electro-Optical Engineering, College of Electrical and Computer Engineering,
National Yang Ming Chiao Tung University, Hsinchu 30010, Taiwan

CORRESPONDING AUTHOR: Y.-C. YUAN (e-mail: twbk.ee09@nycu.edu.tw)

ABSTRACT Gap-type amorphous silicon (a-Si) thin-film transistor (TFT) used as photo sensor has been reported in previous literature. However, the noise behavior of gap-type a-Si TFT is not inspected yet. Therefore, we investigate the noise response of the gap-type a-Si TFT under illumination in this paper. We compare the difference between the results of the gap-type and the conventional-type TFTs. In addition, we analyze it including the perspectives of power spectrum, integral power spectrum, Hooge parameter, fluctuate slope. Finally, we explain the reason for its fluctuate slope transition and review the correlation between noise behavior and photo effect mechanism.

INDEX TERMS Amorphous silicon, gap-type, thin-film transistors (TFTs), noise.

I. INTRODUCTION

In previous research, the mechanism of photo effect in gap-type amorphous silicon (a-Si) thin-film transistor (TFT) is revealed [1] and the implementation in fingerprint recognition is demonstrated as well [2]. The noise, which may affect the performance of sensor, is a crucial factor in specification. Especially for sensing low intensity signal, once the noise level approach to the sensed signal, the signal-to-noise ratio (SNR) would drop significantly and result in low sensing resolution. To investigate the noise behavior of device under different illuminated intensities, we experiment the device with signal source analyzer (Agilent Technologies E5052B). Further, we analyze it in perspective of power spectrum density [3], Hooge parameter (α_H) [4], and fluctuate slope [5]. At last, we explain the results of the noise behavior, and discuss the correlation between noise behavior and photo effect mechanism.

II. EXPERIMENTAL RESULTS OF NOISE BEHAVIOR

The fabrication processes of the gap-type a-Si TFTs in this paper are described elsewhere [6] and the schematic of the device is shown in Fig. 1, except for a channel width of 50 μm, a channel length of 10 μm, and gap length of 4μm. The I_D-V_G characteristics of the device under several light intensity illuminated is as shown in Fig. 2.

The experimental setup for noise measurement is as shown in Fig. 3. According to the figure, the gap-type a-Si TFT is placed in shielding box in order to reduce the illumination of ambient light. A white LED is used as the light source in our experiment which is controlled by the waveform generator and the illumination conditions are from dark to 30500 Lux. The drain voltage (V_D) of TFT is biased using Keithley 4200 at 10V and the gate voltage (V_G) is sweeping from −15V to 15V with signal source analyzer (Agilent Technologies E5052B). The drain current is fed into a preamplifier, which is virtually grounded with the source of TFT, and subsequently analyze with signal source analyzer.

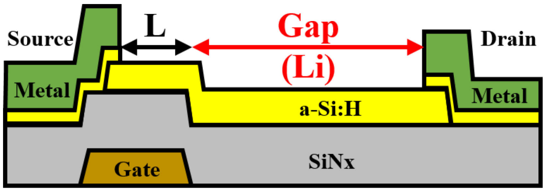


FIGURE 1. Cross-sectional view of gap-type TFT.

Fig. 4 (a) and (b) shows the raw data of power spectrum density (SI) versus frequency under 22.4 Lux and 30500 Lux, representing the low and high illuminated intensities respectively. In addition to seeing the trend of well-known flicker noise (1/f) noise [7], it is worth noticing that the noise increased slightly with higher light intensity.

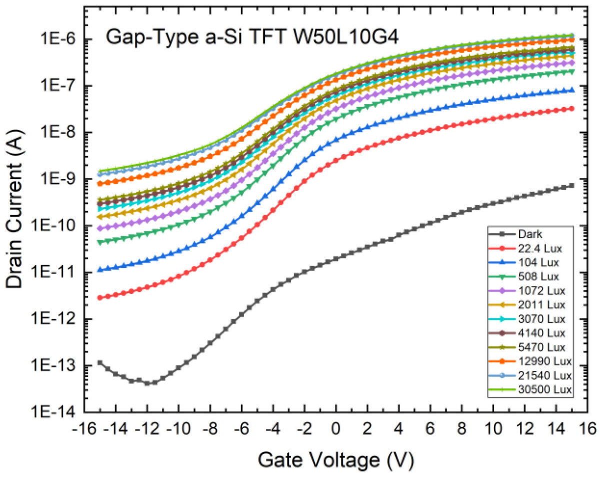


FIGURE 2. I_D-V_G **Characteristics of gap-type TFT.**

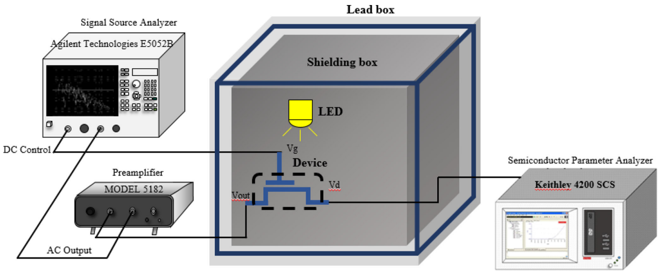


FIGURE 3. Experimental setup of noise measurement.

III. NOISE ANALYSIS

To further discuss the noise behavior, the power spectral integral (SI*) is further calculated and plotted against light intensity in Fig. 5. Interestingly, when the light intensity is lower than 1000 Lux, the power spectral integral (SI*) increases sharply. When the light intensity is higher than 1000 Lux, the increase of the power spectral integral (SI*) is comparably gentle and gradually saturate. This phenomenon may be related to changes in device mechanisms.

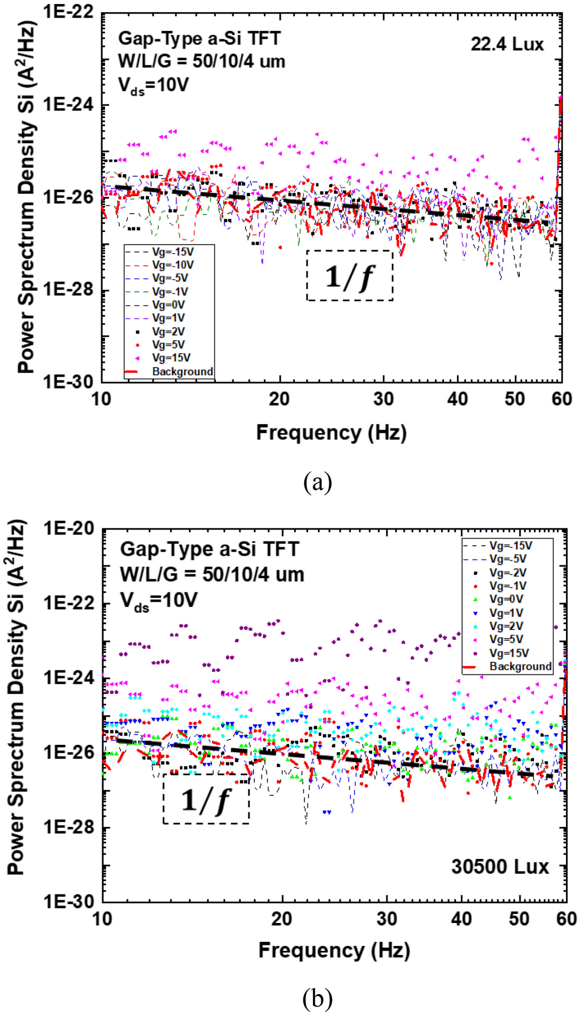
To clarify the reason, we refer to some other well-established noise analysis parameters and methods. One is the Hooge parameter (α_{H}) in Hooge's theory. The reference calculation formulas of Hooge parameter are as equation (1) to (5) [8]:

$$\frac{S_{I_{\mathrm{D}}}(f)}{I_{\mathrm{D}}^2} = \frac{\alpha_{\mathrm{H}}}{f \cdot N}, \tag{1}$$

where $S_{I_D}(f)$ is power spectral density, I_D is drain current, α_H is Hooge parameter, f is frequency, and N is carrier number.

$$\frac{1}{I_D^2} \int_{f_1(Hz)}^{f_2(Hz)} S_{I_D}(f)\ df = \frac{\alpha_H}{N} \int_{f_1(Hz)}^{f_2(Hz)} \frac{1}{f} df \tag{2}$$

$$\frac{S_I^*}{I_D^2} = \frac{\alpha_H}{N} \left(\ln \frac{f_2}{f_1} \right), \tag{3}$$



(a)

(b)

FIGURE 4. Power spectral density of gap-type a-Si TFT under illumination of (a) 22.4Lux and (b) 30500Lux.

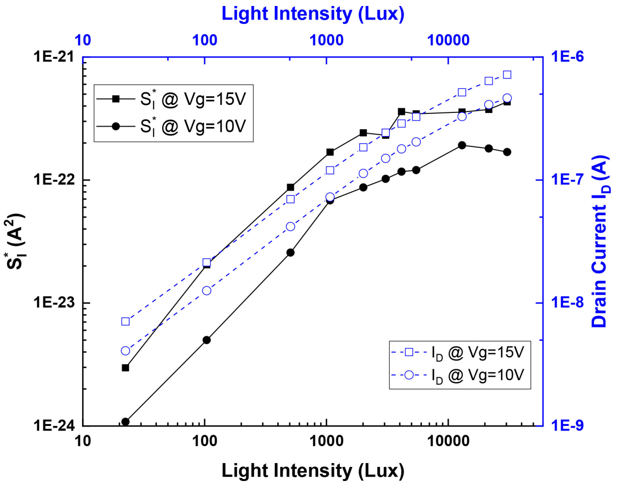
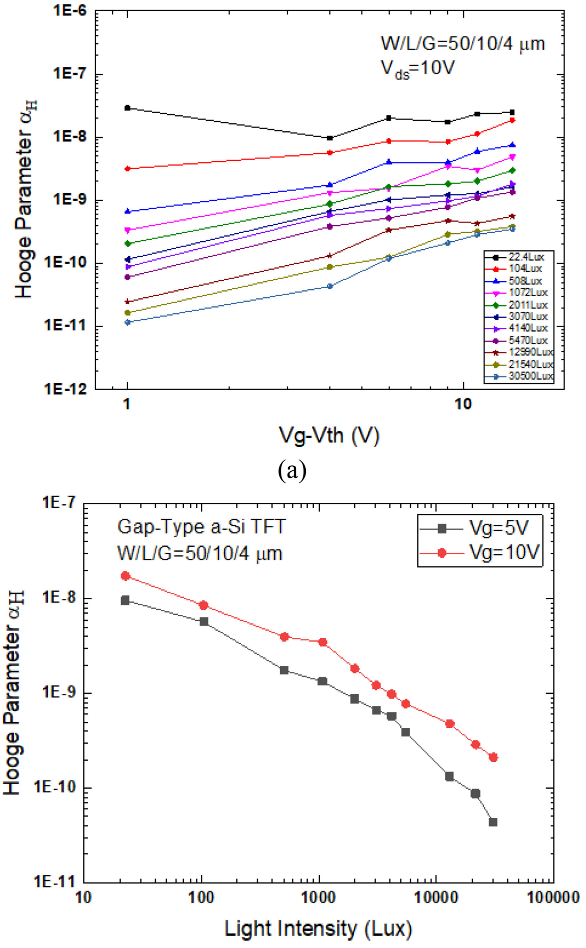


FIGURE 5. Power spectral integral (SI*) versus light intensity (Lux).

where $S_I{}^*$ is power spectral integral.

$$N = \frac{WL\varepsilon}{qd}(V_{GS} - V_{th}), \tag{4}$$



(b)

FIGURE 6. **Hooge parameter against (a) over-drive voltage (V_G-V_{th}) (b) light intensity (Lux).**

where *W* is channel width, *L* is channel length, *ε* is dielectric constant, q is elementary charge, and d is the thickness of gate insulator.

Finally, we can derive equation (5) from (1) to (4).

$$\alpha_H = \frac{S_I^*}{I_D^2}\frac{WL\varepsilon}{qd\ln\frac{f_2}{f_1}}(V_{GS} - V_{th}) \tag{5}$$

The extracted Hooge parameters versus gate voltage and Hooge parameter versus light intensity are plotted in Fig. 6(a) and (b), respectively. In Fig. 6(a), under the low light intensity of 22.4lux, the result presents a constant ratio of α_H/V_g-V_{th}, which is similar to that of conventional a-Si TFT [9], [10]. When the illuminated light intensity increases, the ratio of α_H/V_g-V_{th} shows a downward trend. While it could be plainly viewed that the value of the Hooge parameter becomes smaller as the illuminating intensity getting stronger in Fig. 6(b).

According to (5), it implies the ratio of S_I^*/I_D^2 is the dominant variable of the Hooge parameter. Based on the S_I and S_I^* results as mentioned above, we knew that the noise does rise, but meanwhile, the value of quadratic I_D has also risen sharply under illumination. As a result, the Hooge parameter gradually decreases with the higher light intensity.

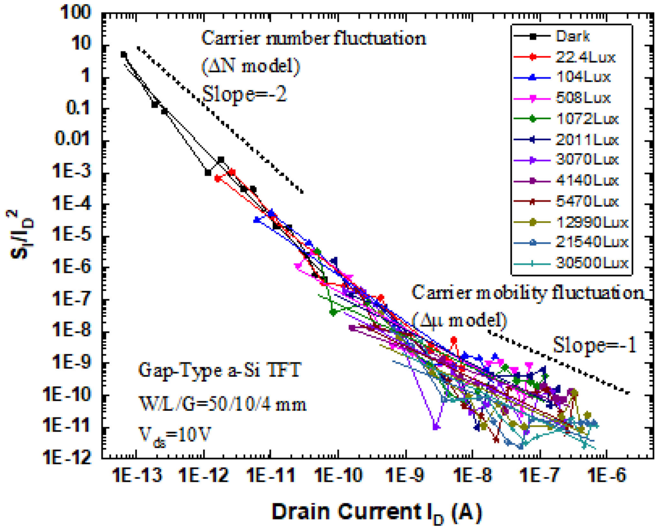


FIGURE 7. **Curves of S_I^*/I_D^2 versus drain current under different light intensities with the trends of carrier number fluctuation (Δn) and carrier mobility fluctuation (Δμ).**

In addition to the Hooge parameter, the other method to analyze noise is the fluctuation model [11]. The experimental results are delineated in Fig. 7. Overall, the data shows that the fluctuation slope changes from −2 to −1 as the drain current and light intensity increase.

According to the fluctuation model in previous research, the slope of fluctuation nearly equals −2, representing that the noise behavior is imputed to the carrier number fluctuation (Δn) model. When the slope of fluctuation nearly equals −1, it represents that the noise behavior is attributed to the carrier mobility fluctuation ($\Delta\mu$) model [12]. The results show that the noise behavior will change from the carrier number fluctuation (Δn) model to the carrier mobility fluctuation ($\Delta\mu$) model. Under low light intensity, the barrier lowering mentioned in the photosensitive mechanism section is insignificant. A comparatively higher barrier will obstruct the transmission of electrons, resulting in low electron mobility. The photocurrent mainly comes from the increase in the number of carriers generated by the illumination. Therefore, the noise behavior is dominated by carrier number fluctuation. While under high light intensity, the barrier lowering is comparably significant, the energy barrier that restrains electrons' transmission is lowered accordingly. In addition to the increased number of carriers owing to the illumination, the electron mobility has also apparently increased. Therefore, the noise behavior is dominated by carrier mobility fluctuation.

Based on the proposed mechanism, the noise behavior of gap-type a-Si TFT can also be explained consistently.

IV. CONCLUSION

In this paper, we experiment the noise measurement of the gap-type a-Si TFT under illumination. Although the photo-induced noise increases, the photo-induced current reflected on device is also greatly increased, resulting in a trend of decreasing in Hooge parameter with respect to the increasing light intensity. In addition, the carrier number fluctuation under low light intensity illumination will transit to mobility fluctuation when the light becomes stronger. We explain the transition point as the threshold of the photo-induced barrier lowering in the energy level of gap-type a-Si TFT. The transition of noise behavior in gap type a-Si TFT is consistent with the barrier lowering theory in its mechanism.

REFERENCES

[1] Y.-H. Tai, C.-C. Tu, Y.-C. Yuan, Y.-J. Chang, P.-C. Wang, and Y.-W. Kuo, “The photosensitive mechanism of gap-type amorphous silicon TFT,” *IEEE Trans. Electron Devices*, vol. 68, no. 12, pp. 6177–6181, Dec. 2021.

[2] Y.-H. Tai, C.-C. Tu, Y.-C. Yuan, Y.-J. Chang, M.-H. Hsu, and C.-Y. Chuang, “Light-controlled gap-type TFT used for large-area under-screen fingerprint sensor,” *IEEE J. Electron Devices Soc.*, vol. 9, pp. 517–520, 2021, doi: 10.1109/jeds.2021.3076832.

[3] J.-M. Lee, W.-S. Cheong, C.-S. Hwang, I.-T. Cho, H.-I. Kwon, and J.-H. Lee, “Low-frequency noise in amorphous Indium–Gallium–Zinc-Oxide thin-film transistors,” *IEEE Electron Device Lett.*, vol. 30, no. 5, pp. 505–507, May 2009, doi: 10.1109/led.2009.2015783.

[4] F. N. Hooge, “1/f noise is no surface effect,” *Phys. Lett. A*, vol. 29, no. 3, pp. 139–140, 1969.

[5] Y. Liu, H. He, R. Chen, Y.-F. En, B. Li, and Y.-Q. Chen, “Analysis and simulation of low-frequency noise in indium-zinc-oxide thin-film transistors,” *IEEE J. Electron Devices Soc.*, vol. 6, pp. 271–279, 2018.

[6] Y.-H. Tai, L.-S. Chou, and H.-L. Chiu, “Gap-type a-Si TFTs for front light sensing application,” *J. Display Technol.*, vol. 7, no. 12, pp. 679–683, Dec. 2011.

[7] J. Rhayem, M. Valenza, D. Rigaud, N. Szydlo, and H. Lebrun, “1/f noise investigations in small channel length amorphous silicon thin film transistors,” *J. Appl. Phys.*, vol. 83, no. 7, pp. 3660–3667, 1998, doi: 10.1063/1.366586.

[8] F. Hooge and A. Hoppenbrouwers, “Amplitude distribution of 1/f noise,” *Physica*, vol. 42, no. 3, pp. 331–339, 1969.

[9] J. Rhayem, D. Rigaud, M. Valenza, N. Szydlo, and H. Lebrun, “1/f noise modeling in long channel amorphous silicon thin film transistors,” *J. Appl. Phys.*, vol. 87, no. 4, pp. 1983–1989, 2000, doi: 10.1063/1.372124.

[10] J. M. Boudry and L. E. Antonuk, “Current-noise-power spectra of amorphous silicon thin-film transistors,” *J. Appl. Phys.*, vol. 76, no. 4, pp. 2529–2534, 1994, doi: 10.1063/1.357614.

[11] L. K. J. Vandamme, L. Xiaosong, and D. Rigaud, “1/f noise in MOS devices, mobility or number fluctuations?” *IEEE Trans. Electron Devices*, vol. 41, no. 11, pp. 1936–1945, Nov. 1994, doi: 10.1109/16.333809.

[12] P. Wang *et al.*, “1/f noise in as-processed and proton-irradiated AlGaN/GaN HEMTs due to carrier number fluctuations,” *IEEE Trans. Nucl. Sci.*, vol. 64, no. 1, pp. 181–189, Jan. 2017, doi: 10.1109/tns.2016.2636123.

YA-HSIANG TAI (Senior Member, IEEE) received the B.S. and Ph.D. degrees in electronic engineering from National Chiao Tung University, Taiwan, in 1990 and 1996, respectively. He became a member of Industrial Technology Research Institute/Electronics Research and Service Organization and the TFT LCD Development as a Panel Designer. He joined the project of low temperature polycrystalline silicon (LTPS) thin-film transistor (TFT) development in Prime View International in 2000. In 2001, he entered Toppoly Optoelectronics Corporation, to lead the team of LTPS TFT LCD panel design. He joined the faculty of National Chiao Tung University in 2003, where he is currently a Professor with the Department of Photonics and Institute of Electro-Optical Engineering, College of Electrical and Computer Engineering. His current research emphases are in the areas of TFT device physics, active matrix display panel design, and system on panel and X-ray imager system.

YI-CHENG YUAN received the B.S. degree in physics from National Taiwan Normal University, Taiwan, in 2019, and the M.S. degree from Institute of Electro-Optical Engineering, National Chiao Tung University, Taiwan, in 2021, where he is currently pursuing the Ph.D. degree with the Department of Photonics and Institute of Electro-Optical Engineering, College of Electrical and Computer Engineering. His current research interests include the applications of TFT-based sensing device and high sensitive active pixel sensing circuit.

CHENG-CHE TU received the B.S. degree in physics from National Cheng Kung University, Taiwan, in 2013, and the M.S. degree from the Institute of Electro-Optical Engineering, National Chiao Tung University, Taiwan, in 2018. He is currently pursuing the Ph.D. degree with the Department of Photonics and Institute of Electro-Optical Engineering, College of Electrical and Computer Engineering, National Yang Ming Chiao Tung University, Taiwan. His current research interests include the applications of TFT-based sensing device and high sensitive active pixel sensing circuit.

PIN-CHUN WANG received the B.S. degree in physics from National Sun Yat-sen University, Taiwan, in 2019, and the M.S. degree from the Institute of Electro-Optical Engineering, National Chiao Tung University, Taiwan, in 2021. His research interests include the sensor and gap-type a-Si TFT.