Light-Controlled Gap-Type TFT Used for Large-Area Under-Screen Fingerprint Sensor

YA-HSIANG TAI¹ (Senior Member, IEEE), CHENG-CHE TU¹, YI-CHENG YUAN¹, YU-JIA CHANG¹, MAO-HSIU HSU², AND CHE-YU CHUANG³

¹ Department of Photonics and Institute of Electro-Optical Engineering, College of Electrical and Computer Engineering, National Yang Ming Chiao Tung University, Hsinchu 30010, Taiwan
² Department of Marketing, Focal-Tech Electronics Corporation, Hsinchu 30078, Taiwan
³ Department of Product Technology Development, HannsTouch Solution Incorporation, Tainan 74149, Taiwan

ABSTRACT In the fierce market competition of different biometric methods in smartphones, where consumers are pursuing a high screen ratio, optical fingerprint recognition under OLED screen is a well-established approach. However, using thin-film transistor (TFT) technology to make large-area optical sensors generally has the issue of low sensitivity, which will make the signal difficult to be read out. In this paper, we propose to use gap-type TFT with high photosensitivity current and process compatible with display panels as the sensing device to build the sensing array. The pixel circuit can be simplified to structure containing only of two thin-film transistors (TFTs). Using this gap-type TFT sensing array under OLED panel for fingerprint recognition is proven to be effective by the clear images captured with the readout system.

INDEX TERMS Fingerprint sensor, gap-type, photocurrent, thin film transistor (TFT).

I. INTRODUCTION Nowadays, smartphone is an indispensable mobile device in human daily life. Many functions and applications require biometrics recognition to ensure personal information security. Biometrics recognition methods include fingerprint and face ID [1]. In comparison, the false rates of fingerprint recognition are relatively low in practical use. Therefore, fingerprint recognition is an indispensable function for smartphone. In addition, consumers want to maximize the screen-to-body ratio of smartphone. Using the optical sensors under screen is a successful approach. Up to now, only the sensing device made in IC can be sensitive and fast enough to fit this application. However, the cost of IC prevents it from being large in area. Users somewhat difficult to find the location of the IC sensor behind display if its area is small. Therefore, the sensor in large-area made on thin-film transistor (TFT) substrate is expected to replace IC sensor by the smartphone makers [2] and [3]. There are several photosensitive devices can be made on the same substrate of TFT, including PIN diode [4], phototransistor [5]–[7], gap-type TFTs [8] and [9]. We consider that gap-type TFT is the best optical device in the under-screen fingerprint sensor for its good sensitivity and low cost owing to the high photocurrent and fully TFT-compatible process [10] and [11]. In this paper, a system with the gap-type TFT for the optical sensing array, the array under OLED panel with collimator in between, and the readout circuit is built to demonstrate the good performance in fingerprint image capture.

II. GAP-TYPE TFT CHARACTERISTIC AND MECHANISM The cross-sectional view of gap-type TFT is shown in Fig. 1, and the characteristics are shown in Fig. 2. The size of the device is 10 µm in both channel width (W) and length (L), and the gap length (Li) is 4 µm. Its process is identical to that of the conventional amorphous silicon TFT [10]. As the transfer curves shown in Fig. 2(a), the light response of drain current (I_D) can be observed no matter what the gate voltage (V_G) is biased, but it is preferred to use the much high photocurrent when V_G is positive and large. The curves of I_D versus drain voltage (V_D) shown in Fig. 2(b) give another aspect of this device. Varying light intensity with...
$V_G$ fixed at 5V, $I_D$ increases linearly with $V_D$ before it gets a saturation value. This behavior is very similar to a typical $I_D$-$V_D$ characteristic of a normal transistor. In addition, the trend of photocurrent to light intensity at fixed biases of $V_G$ and $V_D$ is illustrated in Fig. 2(c).

The energy band diagrams shown in Fig. 3 are used to explain the light response of the gap-type TFT. When the device is biased at $V_D > 0$, the illumination can generate electron-hole pairs in the active layer. As shown in Fig. 3(a), when $V_G$ lower than flat band voltage ($V_{FB}$), the holes and electrons move to the source and drain electrodes, respectively. The photo effect in this condition resembles that in a photodiode. When $V_G$ is higher than $V_{FB}$, as shown in Fig. 3(b), the light-generated electrons move to the drain electrode as well, but the light-generated holes accumulate at the junction of the gate-controlled channel and the gap. The hole accumulation can lower the energy barrier at the junction, which limits the electrons pass through. The higher light intensity can make the barrier lower, which brings about the light-controlled $I_D$ of the gap-type TFT. The first increase in $V_D$ can provide higher horizontal electric field in the gap to separate more photo-induced carriers. When $V_D$ is large enough, the photo-induced carriers is limited by the incident photons, which results in the $I_D$-$V_D$ characteristics shown in Fig. 2(b).

### III. FINGERPRINT SENSING SYSTEM

The configuration of the gap-type TFT sensing array with its readout circuit is shown in Fig. 4. The pixel circuit is composed of two TFTs, including a gap-type TFT and a normal TFT. Gap-type TFT is used as a photosensitive device, while normal TFT is used as a switch to cut off the current from the unselected gap-type TFT. The simple pixel structure is beneficial for high density. The readout circuit includes analog front end (AFE) IC of Texas Instruments AFE0064 to convert the sensing current into an analog voltage by an integrator, and analog-to-digital convertor (ADC) IC of Analog Devices AD7274 to convert analog voltage into digital code. Unlike the conventional operation of TFT sensing array, which needs long integration time ($t_{int}$) to accumulate enough photo charge as shown in Fig. 5(a), the photocurrent of the gap-type TFT is high enough to be instantly read out in one row-selection time as shown in Fig. 5(b). Thus, the operation of the array is to simply scan the rows, which is implemented by the gate driver on panel. For example, the photocurrent $I_{photo}$ is $1.944 \times 10^{-8}$A at the light intensity of 1Lux, when the read time $t_{read}$ is set at 200µs, and the integrate capacitance $C_{int}$ is chosen to be 1.7143pF, the output voltage $V_{out}$ is calculated to be 2.268V by (1):

$$|V_{out}| = \frac{I_{photo} \times t_{read}}{C_{int}}$$  \hspace{1cm} (1)

The large signal and fast readout brought by the high photocurrent of the gap-type TFT provides the great advantages in the application of fingerprint recognition.
The specifications of the fingerprint sensor array are organized in Table 1. The photograph of the actually built sensing system taken from the front and back sides are shown in Fig. 6(a) and (b) respectively. The collimator is sandwiched between OLED panel and the gap-type TFT sensing array, as shown in Fig. 6(c). The sensing array connects to the readout circuit via flexible printed circuit (FPC). The fingerprint signal is acquired by the readout circuit and fed to control unit. The captured images of some fingerprint are shown in Fig. 6(d), which are processed by background subtraction and image enhancement through algorithms. The ridges and valleys of fingerprint can be clearly seen.

**IV. CONCLUSION**

The high photo-sensing current of the gap-type TFT is suitable for applications in under-screen fingerprint sensing, especially for those requiring fast readout. The common manufacturing process enables the large area and low cost. The simple pixel structure is not only favorable for high-density sensor, but also useful for integrating the sensing function in displays.

**TABLE 1. Fingerprint sensor array specification.**

| Specification                     | Value          |
|-----------------------------------|----------------|
| Pixel Per Inch (PPI)              | 508 PPI        |
| Resolution (HxV)                  | 160 x 160      |
| Fingerprint Sensing Window        | 26mm x 15mm    |
| Active Area (AA)                  | 8mm x 8mm      |
| Pixel Size                        | 50µm x 50µm    |
| Readout Time (t<sub>read</sub>)   | 175µs          |

**FIGURE 3.** Band diagram of gap-type TFT (a) $V_G < V_{FB}$ (b) $V_G > V_{FB}$.

**FIGURE 4.** Gap-type TFT sensing array with its readout circuit.

**FIGURE 5.** Timing chart of (a) conventional (b) instantly readout.

**FIGURE 6.** Fingerprint sensing system (a) front view (b) back view (c) cross-section view and (d) captured fingerprint images.
REFERENCES

[1] D. Kim, M. Hernandez, J. Choi, and G. Medioni, “Deep 3D face identification,” in Proc. IEEE Int. Joint Conf. Biometrics (IJCB), Denver, CO, USA, Oct. 2017, pp. 133–142, doi: 10.1109/BIAS.2017.8272691.

[2] K. S. Karim, P. Servati, and A. Nathan, “High voltage amorphous silicon TFT for use in large area applications,” Microelectron. J., vol. 35, no. 3, pp. 311–315, Mar. 2004, doi: 10.1016/S0026-2692(03)00196-4.

[3] D. Tordera et al., “A high-resolution thin-film fingerprint sensor using a printed organic photodetector,” Adv. Mater. Technol., vol. 4, no. 11, Sep. 2019, Art. no. 1900651, doi: 10.1002/admt.201900651.

[4] T. Eguchi et al., “24.2: A 1300-dpi optical image sensor using an a-Si:H photo diode array driven by LTPS TFTs,” in SID Int. Symp. Dig. Tech. Papers, vol. 38, May 2007, pp. 1097–1100, doi: 10.1109/SID.2007.765029.

[5] H. Xu, J. Wu, Q. Feng, N. Mao, C. Wang, and J. Zhang, “High responsivity and gate tunable graphene-MoS2 hybrid phototransistor,” Small, vol. 10, no. 11, pp. 2300–2306, Jun. 2014, doi: 10.1002/smll.201303670.

[6] K. Wang, H. Ou, J. Chen, A. Nathan, S. Z. Deng, and N. S. Xu, “3-D dual-gate photosensitive thin-film transistor architectures based on amorphous silicon,” IEEE Trans. Electron Devices, vol. 64, no. 12, pp. 4952–4958, Dec. 2017, doi: 10.1109/TED.2017.2763020.

[7] H. Ou, K. Wang, J. Chen, A. Nathan, S. Z. Deng, and N. S. Xu, “Dual-gate photosensitive FIN-TFT with high photoc conducive gain and near-UV to near-IR responsivity,” in Proc. IEEE Int. Electron Devices Meeting (IEDM), San Francisco, CA, USA, Dec. 2016, pp. 814–817, doi: 10.1109/IEDM.2016.7838529.

[8] 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, doi: 10.1109/JDT.2011.2164054.

[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.2011.2135938.

[10] Y.-H. Tai, C.-C. Tu, and S. Yeh, “Using amorphous silicon gap-type thin film transistor as ambient light sensors and proximity sensors for smartphones,” IEEE Sensors Lett., vol. 3, no. 10, pp. 1–4, Oct. 2019, doi: 10.1109/LSENS.2019.2940763.

[11] C.-C. Tu, S.-Y. Wu, and Y.-H. Tai, “P-10: Advantages of active pixel circuit using gap-type TFT as the photo device to sense low intensity light,” in SID Symp. Dig. Tech. Papers, vol. 51, Sep. 2020, pp. 1346–1349, doi: 10.1002/sdtp.14133.

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 joined the project of low temperature polycrystalline Si (LTPS) thin-film transistor (TFT) development with 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 emphasis are in the areas of TFT device physics, active matrix display panel design, and system on panel and X-ray imager system. He became a member of Industrial Technology Research Institute/Electronics Research & Service Organization and the TFT LCD development as a Panel Designer.

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, 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 device and high sensitive active matrix sensing circuit.

YI-CHENG YUAN received the B.S. degree in physics from National Taiwan Normal University, Taiwan, in 2019, and the M.S. degree from the 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.

YU-JIA CHANG received the B.S. degree in physics from National Sun Yat-sen University, Taiwan, in 2018, and the M.S. degree from the Institute of Electro-Optical Engineering from National Chiao Tung University, Taiwan, in 2021. His research interests include the sensor and a-Si TFT.

MAO-HSIU HSU received the Ph.D. degree from the Department of Electronic and Computer Engineering, National Taiwan University of Science and Technology, Taiwan, in 2005.

In 2019, he joined FocalTech Electronics as a Senior Technical Manager with Hisinchu Science Park, and he was an Assistant Professor with the Department of Information and Telecommunications Engineering, Taiwan Ming Chuan University, in 2006. He joined Motorola crystal filter and oscillator design as an Engineer in 1997, and he was a Staff Engineer with Chunghwa Telecom Company, Ltd. from 1998 to 2005. From 2007 to 2012, he worked with Foxconn, San Jose, CA, USA. In 2013, he was an Inpaq USA Site Country Manager. He served in a Senior Manager with Primax Taiwan from 2014 to 2019. He owned rich sensor and optical signal process and artificial algorithm experience in fingerprint and face recognition sensor IC system design. He has published over 50 technical papers and patents. His current research interests include the applications of high sensitive active matrix sensing system for face ID and large and thinnest optical fingerprint on 5G mobiles.

CHE-YU CHUANG received the B.Sc. degree in electrical engineering from the National Kaohsiung University of Applied Sciences, Taiwan, in 2004, and the M.Sc. degree in electrical engineering from the National Yunlin University of Science and Technology, Taiwan, in 2006. He is the Account Assistant Manager with the Product Technology Development Department, HannsTouch Solution Inc., where he has been engaging in the research and development in drive circuit design for electronic shelf labels, touch sensor, and fingerprint sensor since 2015. Subsequently, he joined the HannStar Display Corporation until August 2015. During which he experienced as an Engineer, a Senior Engineer, and the Technical Assistant Manager with the System Design Department responsible for team and project management and the research and development in LCD drive circuit.