JOURNAL OF THE
ELECTRON DEVICES SOCIETY

Received 21 November 2017; accepted 22 November 2017. Date of publication 8 January 2018; date of current version 26 January 2018.
The review of this paper was arranged by Editor A. Nathan.

Digital Object Identifier 10.1109/JEDS.2018.2790954

Integrated Active-Matrix Capacitive Sensor Using a-IGZO TFTs for AMOLED

YUANFENG CHEN, DI GENG, AND JIN JANG (Member, IEEE)

Department of Information Display, Advanced Display Research Center, Kyung Hee University, Seoul 02447, South Korea

CORRESPONDING AUTHOR: J. JANG (e-mail: jjang@khu.ac.kr)

This work was supported in part by the Industrial Strategic Technology Development Program under Grant 10045269, and in part by the Development of Soluble TFT and Pixel Formation Materials/Process Technologies for AMOLED TV through MOTIE/KEIT.

ABSTRACT We report a capacitive touch sensor using a-IGZO TFTs as active components to improve touch sensitivity and output robustness. The output potential difference between touched/untouched states is 1.7 V without readout buffer. Additionally, due to the fully compatible gate driving clocks with conventional active-matrix backplane, the integration of the capacitive touch sensor with AMOLED display without additional driver ICs can be realized. An 8 × 8 array with only one output pin using pixel-by-pixel readout has been developed, which benefits the full flexible applications with simple connection and readout method.

INDEX TERMS a-IGZO, active matrix, capacitive touch, TFT.

I. INTRODUCTION

Amorphous oxide semiconductors (AOSs) are of increasing interest for applications including display, sensor and other transparent flexible electronics [1], [2]. In particular, the amorphous indium-gallium-zinc-oxide (a-IGZO) thin-film- transistors (TFTs) are the most studied for designing integrated circuits used in high-performance and/or flexible devices [3]–[6] due to their high current driving capability [7], [8], flexible substrate friendly low temperature process [9], [10], and high scalability.

On the other hand, touch sensors, especially capacitive type touch sensor, has become one of the most important human machine interfaces in smartphones, PCs and even vehicles due to its advantages in touch accuracy, multi-touch support, and designing form factor compared to other type of touch sensors such as optical and resistive ones. However, there are several drawbacks as described hereinafter that need to be overcome for the use of capacitive touch sensor to large sized liquid-crystal display and active-matrix organic light emitting diode (AMOLED) display. Most of the capacitive touch sensing systems use external driving IC to drive a passive electrode matrix and high precision readout IC to read the tiny capacitance change made by touch events [11]. For example, the in-cell touch, which merges the touch module with the display backplane, has been widely used in mobile displays to simplify the display/touch module [12]. However, passive electrodes are sensitive to environmental noise and interference from the signals of active matrix display, thus a non-overlapping clock timing between touch and display is required [13]. This increases the complexity for driving logic and limits the touch accuracy, maximum display size and resolution. Some sensors use TFTs to improve the output robustness for liquid crystal display [14], but the circuitry is not easy to directly implement to AMOLED display. Additionally, electric field shielding from the cathode of OLED makes it almost impossible for conventional in-cell touch to be implemented in AMOLED display. Furthermore, rigid driver and readout ICs have to be bonded besides the array, thus increasing the difficulties of implementing capacitive touch sensor to full flexible and bendable device.

In this letter we report a capacitive touch sensor using a-IGZO TFTs to achieve high touch sensitivity and robust output. The proposed touch sensor has a set of gate clocks that are fully compatible with the conventional AM backplane. This enables an easy integration of capacitive sensor to AMOLED display without additional touch driving IC. Finally, an 8x8 capacitive sensor array using integrated gate driver and pixel-by-pixel readout method has been demonstrated to evaluate the proposed sensor under AM driving condition.

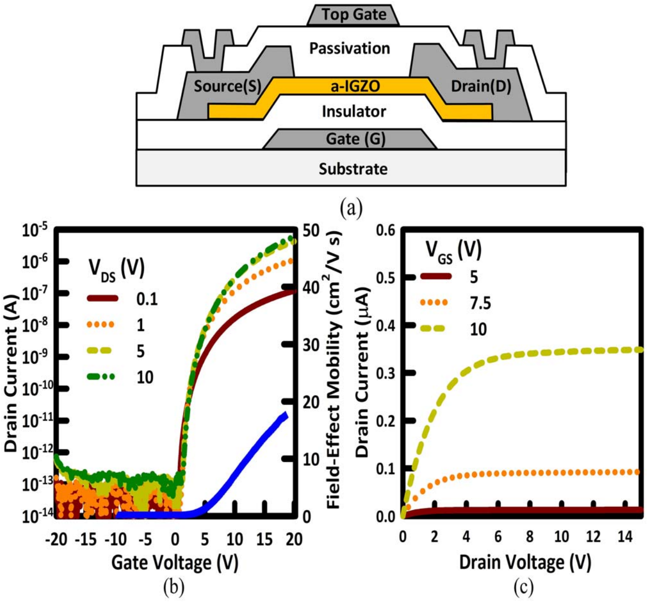

FIGURE 1. (a) Cross sectional view of the BCE a-IGZO double-gate TFT and (b) transfer curve, and (c) output characteristics of the double-sweep TFT with channel L=6μm and W=20μm.

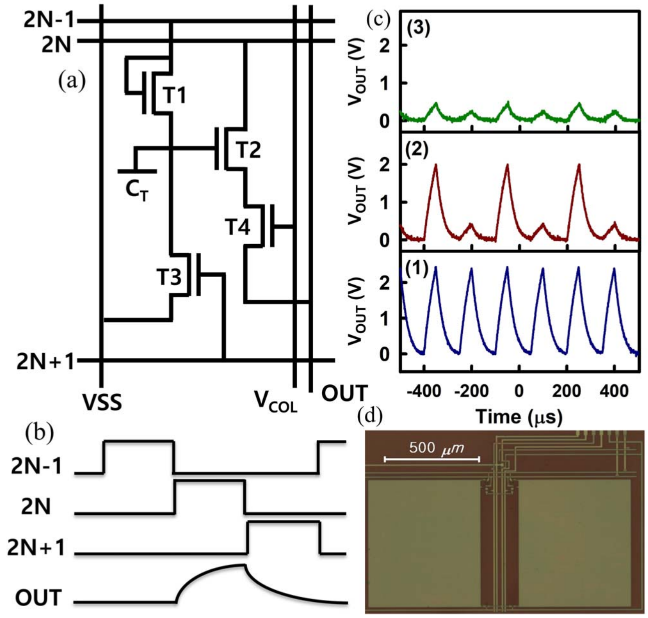

FIGURE 2. (a) Circuit diagram of the capacitive sensor, (b) its driving timing diagram, and (c) measured output waveform from a two-pixel test structure with serial output when (1) untouched (2) one pixel touched (3) both pixels touched. The optical image is shown in (d).

II. EXPERIMENT

The inverted staggered back channel etched (BCE) a-IGZO TFTs with an additional top-gate (TG) are used in this study, as shown in Fig. 1(a). The TG of the double-gate (DG) TFT has offsets with source/drain elctrodes of 1.5 μm each to avoid the introduction of additional parasitic capacitance [15]. The fabrication process is described in detail elsewhere [16], [17]. The bottom gate (BG) and TG insulators are plasma enhanced chemical vapor deposited (PECVD) SiO_2 with respective thicknesses of 250 and 300 nm, giving gate capacitances of 1.38 x 10^{-8} and 1.15 x 10^{-8} F/cm^2, respectively. The total gate capacitance C_{OX} of the DG TFT is calculated considering both BG and TG capacitances. All electrical measurements are performed with the TG electrically shorted to the BG in ambient air under dark and at room temperature. The turn-on voltage V_{ON} is defined as the V_{GS} at which I_{DS} starts to monotonically increase with $V_{DS} = 0.1$ V. The field-effect mobility (μ_{FE}), as a function of V_{GS}, is retrieved from the transconductance $\partial I_{DS}/\partial V_{GS}$ with $V_{DS} = 0.1$ V. All the transient measurements in this study use a direct readout to the oscilloscope by a 10x passive probe without any readout buffer or amplifier. All the touch measurements are performed by touching directly with a human finger.

III. RESULTS AND DISCUSSION

Typical transfer and output characteristics of the fabricated DG a-IGZO TFTs with channel length (L) and width (W) of 6 μm and 20 μm respectively are shown in Fig. 1 (b) and (c). The devices show the μ_{FE} of ~17 cm^2/V·s at $V_{GS} = 20$ V and V_{ON} of ~1.4 V. All circuits reported in this paper use TFTs with L of 6 μm and TG shorted to BG for DG driving.

The most critical stability issue in the proposed sensor is the negative gate bias stress under illumination because it works with a very small duty cycle in AM backplane. As the stability of our DG-driven a-IGZO TFTs is found to be excellent due to the achievement of bulk-accumulation in our previous study [16], characteristics of the DG-driven TFTs presented herein are also stable during circuit operation.

Fig. 2(a) shows the circuit diagram of the proposed capacitive touch sensing circuit. It consists of 4 TFTs and one touch electrode. The touch sensing capacitor C_T is formed between the touch electrode and touch object. T1 is a pre-charging TFT which charges C_T during the pre-charging period. T2 is output driving TFT that converts the touch sensing voltage on C_T to current. As T2 can significantly improve the output drivability, the robust output with large voltage variation between touched/untouched states can be achieved. T3 is the reset TFT that discharges C_T and turns off T2 after the readout period. T4 is applied only when a pixel by pixel readout is applied. Detail of this readout method will be discussed later.

All the TFTs are with a channel length of 6 μm, while the channel width of T1 to T4 are 5, 10, 5, 10 μm, respectively. Timing diagram of the driving clocks and output are shown in Fig. 2(b). One complete sensing cycle of the proposed circuit can be divided into three periods, which are pre-charging, readout and reset. They are controlled by three clocks called 2N-1, 2N and 2N+1 in the diagram. During the pre-charging period, clock 2N-1 goes high and charges C_T through T1 to a high voltage level named V_1. When a certain clock high voltage V_{DD} is given, V_1 at the end of pre-charging period mainly depends on the duration, current drivability of T1, and capacitance of C_T. Therefore, by selecting proper value of clock duration and channel width of T1, V_1 can have high sensitivity on the change of C_T between touched and untouched states. As C_T increases significantly when the electrode is touched, V_1 is much higher in an untouched sensor than a touched one. As for the readout period, clock 2N goes high and the voltage on C_T will be bootstrapped through the gate-to-drain overlap capacitance (C_{GD}) of T2. Therefore, gate voltage of T2 in readout period can be expressed as,

$$V_2 = V_1 + V_{DD}\frac{C_{GD}}{C_T + C_{GD}} \quad (1)$$

According to eq. (1), V_2 will be higher if C_T is small, which means the touch-induced C_T variation has been again converted into the gate voltage variation of T2 at the beginning of readout peroid. Then, T2 turns on at the readout period, and the output current level depends on the touch state of C_T by the two-step capacitance-voltage conversion described above. Compared to previous work [14] that uses the bias voltage of common electrode to pre-charge the touch electrode, charging by gate clock gives better output drivability due to the higher gate voltage than common bias. Finally, clock 2N+1 turns on T3 during the reset period to discharge C_T and T2 is switched off. This prevents potential interference to output of other rows. Fig. 2(c) shows the measured output waveform from the fabricated test structure containing two sensing pixels, which share one output line with non-overlapping output periods one after another. Optical image of this fabricated test structure is shown in Fig. 2(d). The circuit was measured without a circular polarizer on the top because a much smaller sized touch electrode compare to in real displays is applied due to sample size limit. Thus the layer thickness on the top of touch electrode also needs to be reduced in order to achieve a touch capacitance similar with in real displays. The size of each touch sensing electrode is 0.37 mm^2 and the thickness of individual layers between the touch sensing electrode and touch object is about 20 μm with a dielectric constant about 3.4, which gives a maximum C_T of around 0.55 pF. This value is comparable to the capacitance in real applications. As the touch capacitance is the key of the behavior of the touch sensor, we expect consistent performance of the proposed sensing circuit in real AMOLED display with polarizer and cover glass on the top by scaling up the touch electrode. A V_{DD} of 20V and a V_{SS} of 0V have been applied during this measurement. When both pixels are untouched, output goes high at about 2V during all readout periods as shown in Fig. 2(c)(1). When one of the two pixels is touched, the output belongs to this pixel remains low at less than 300mV while the output of the untouched pixel keeps going high, as shown in Fig. 2(c)(2). When both pixels are touched, the output keeps low during all the readout periods as in Fig. 2(c)(3). The proposed touch sensing circuit shows an output voltage variation between touched/untouched states (ΔV_{OUT}) of 1.7V,

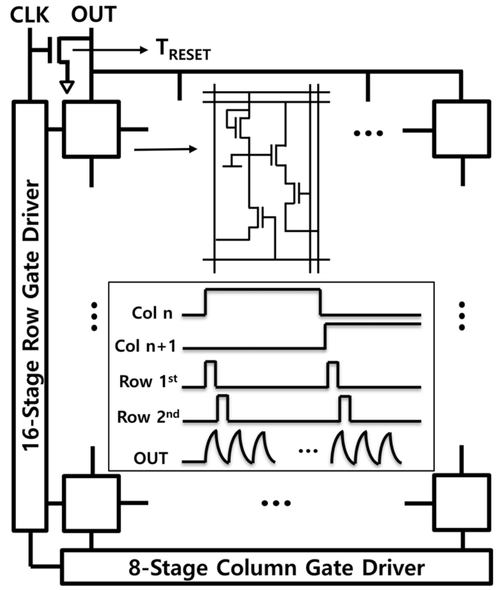

FIGURE 3. Block diagram of the 8x8 active matrix capacitive sensor array and (inset) its timing diagram.

which is sufficient for direct readout without high precision amplifiers.

For further investigating the characteristics of the proposed circuit when integrated with an AM array, an 8 x 8 sensor with integrated column and row gate drivers [18] using pixel by pixel readout method has been designed and fabricated. Fig. 3 shows the block diagram of its structure together with the timing diagram in the inset. The column gate driver is working under a 'slow' speed and during an enable period of its one stage, the 'fast' row gate driver will finish one scan from the first stage to the last for each sensor at this column. Only one of the many sensors will be selected at one time, thus this method is called pixel by pixel readout [19]. Output from all pixels are connected together to one single line to reduce the number of pins required for output, and one reset TFT will discharge this only output line during each pre-charge period of the sensing pixels. Fig. 4(a) shows the optical image of the fabricated 8 x 8 full-integrated capacitive sensor array with a 16-stage row gate driver and an 8-stage column gate driver. Total area of the array incluing gate drivers is about 0.7 cm^2. By comparing output voltage of two frames between touched and untouched states, a mapped ΔV_{OUT} is shown in Fig. 4(b). The touched point shows a ΔV_{OUT} of 0.7V under a V_{DD} of 10V. Different from conventional capacitive sensor, each proposed sensing circuit only works when the scan lines that directly drive this circuit are enabled. As a result, the noise from other scan lines, which always remain low when this sensing circuit works, is negligible. Also, due to the short sensing cycle as long as the scan time for just one row, certain data noise that influence the touch sensing output can be easily pick out and compensated. It is noted that although the pixel-by-pixel readout is good for flexible electronics due to the reduced

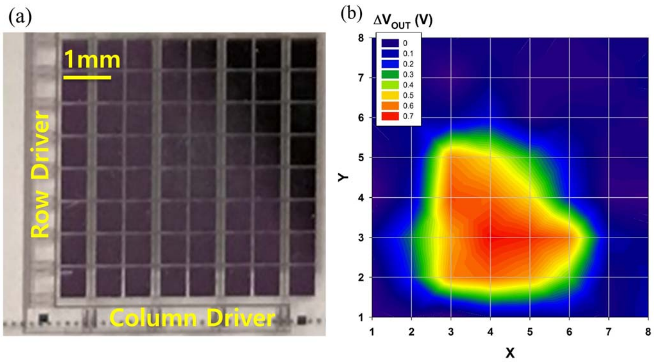

FIGURE 4. **(a) Optical image and (b) measured output of the 8x8 matrix sensor with finger touching the array.**

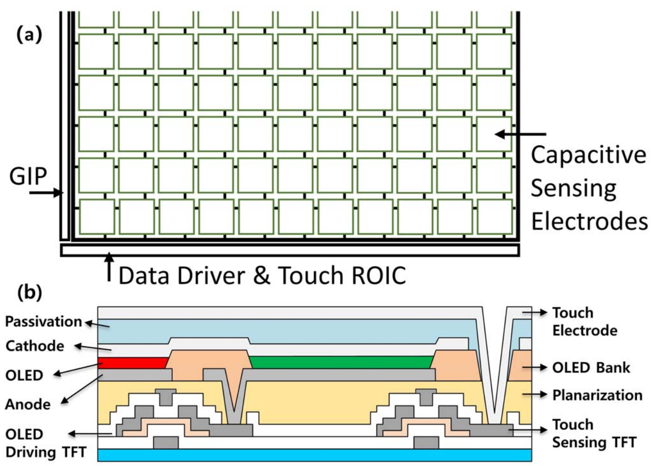

FIGURE 5. **Conceptional (a) top view and (b) cross-sectional view of the proposed touch sensing circuit integrated with top-emission AMOLED display.**

number of output pins, the additional column gate driver will increase the system complexity as well as bezel width. In this case, we can convert the readout to a conventional row-by-row method by removing the column gate driver and the column swithing TFT T4 in the sensing circuit.

Fig. 5 (a) and (b) show the conceptional top view and cross sectional view of top-emission AMOLED display integrated with the touch sensors developed in this work, respectively. The touch sensing circuits share the gate driver in panel (GIP) with the display backplane and have individual capacitive sensing electrode for each of them as shown in Fig. 5 (a). The self-capacitive touch electrodes reduce the parasitic capacitance with the cathode layer of OLED compare to conventional mutual-capacitive electrodes that usually cover the whole column/row of the display. Moreover, SPICE simulation result shows that the proposed circuit is able to maintain an output voltage variation of >200 mV between touched/untouched states even when the parasitic capacitance is 10 times larger than the maximum touch capacitance. As a result of the reduced parasitic capacitance and enhanced sensing robustness, the proposed circuit guarantees performance advantage over conventional capacitive sensor even when tightly integrated with AMOLED displays. It also has to be mentioned that even the proposed touch circuit can be integrated to bottom-emission AMOLED without process issue within state of the art, via holes through OLED layers without damaging OLED as shown in Fig. 5(b) is necessary in order to integrate this touch sensing circuit into top-emission AMOLED displays. This process technique exceeds the present state of the art and still needs to be developed.

IV. CONCLUSION

Advantages of the proposed touch sensor lies on three aspects. First, timing of the row driving signals are fully compatible with the gate driving inputs, which means the proposed capacitive sensing circuit can be integrated into AMOLED backplane without additional touch driver IC and gate lines. Second, touch sensing circuit area is minimized due to the high crossing current of DG driving a-IGZO TFTs. Finally, unlike conventional two-layered X-Y passive touch sensing electrodes, the single layered self-capacitive touch electrode structure can further reduce the paracitic capacitance and system complexity. We have demonstrated a novel capacitive touch sensing circuit using a-IGZO TFTs which can be easily integrated with AMOLED backplane. Measurement of the fabricated 2-pixel test structure and 8 x 8 array showed the robust output for touch detection. This result confirms one possible approach of integrating capacitive touch sensing to AMOLED displays.

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, Aug. 2010, Art. no. 044305, doi: 10.1088/1468-6996/11/4/044305.

[2] J. S. Park, W.-J. Maeng, H.-S. Kim, and J.-S. Park, "Review of recent developments in amorphous oxide semiconductor thin-film transistor devices," *Thin Solid Films*, vol. 520, no. 6, pp. 1679–1693, Jan. 2012, doi: 10.1016/j.tsf.2011.07.018.

[3] D. Geng *et al.*, "67.1: Distinguished student paper: 40 um-pitch IGZO TFT gate driver for high-resolution rollable AMOLED," *Soc. Inf. Display*, vol. 44, no. 1, pp. 927–930, Jun. 2013, doi: 10.1002/j.2168-0159.2013.tb06373.x.

[4] M. Mativenga, M. H. Choi, J. W. Choi, and J. Jang, "Transparent flexible circuits based on amorphous-indium–gallium–zinc–oxide thin-film transistors," *IEEE Electron Device Lett.*, vol. 32, no. 2, pp. 170–172, Feb. 2011, doi: 10.1109/LED.2010.2093504.

[5] D. Geng, Y. F. Chen, M. Mativenga, and J. Jang, "30-μm pitch oxide TFT-based gate driver design for small-size, high-resolution, and narrow-bezel displays," *IEEE Electron Device Lett.*, vol. 36, no. 8, pp. 805–807, Aug. 2015, doi: 10.1109/LED.2015.2445319.

[6] M. J. Seok, M. Mativenga, D. Geng, and J. Jang, "Achieving high performance oxide TFT-based inverters by use of dual-gate configurations with floating and biased secondary gates," *IEEE Trans. Electron Devices*, vol. 60, no. 11, pp. 3787–3793, Nov. 2013, doi: 10.1109/TED.2013.2280912.

[7] Y. Chen, D. Geng, T. Lin, M. Mativenga, and J. Jang, "Full-swing clock generating circuits on plastic using a-IGZO dual-gate TFTs with pseudo-CMOS and bootstrapping," *IEEE Electron Device Lett.*, vol. 37, no. 7, pp. 882–885, Jul. 2016, doi: 10.1109/LED.2016.2571321.

[8] S. Lee, J. Shin, and J. Jang, "Top interface engineering of flexible oxide thin-film transistors by splitting active layer," *Adv. Funct. Mater.*, vol. 27, no. 11, Mar. 2017, Art. no. 1604921, doi: 10.1002/adfm.201604921.

[9] M. Mativenga, D. Geng, B. Kim, and J. Jang, "Fully transparent and rollable electronics," *ACS Appl. Mater. Interfaces*, vol. 7, no. 3, pp. 1578–1585, Jan. 2015, doi: 10.1021/am506937s.
[10] S. Lee, D. Jeong, M. Mativenga, and J. Jang, "Highly robust bendable oxide thin-film transistors on polyimide substrates via mesh and strip patterning of device layers," *Adv. Funct. Mater.*, vol. 27, no. 29, Aug. 2017, Art. no. 1700437, doi: 10.1002/adfm.201700437.
[11] K.-D. Kim *et al.*, "A capacitive touch controller robust to display noise for ultrathin touch screen displays," in *Proc. IEEE Int. Solid-State Circuits Conf.*, San Francisco, CA, USA, Feb. 2012, pp. 116–117, doi: 10.1109/ISSCC.2012.6176943.
[12] J.-H. Yang, S.-C. Jung, Y.-S. Son, S.-T. Ryu, and G.-H. Cho, "A noise-immune high-speed readout circuit for in-cell touch screen panels," *IEEE Trans. Circuits Syst. I, Reg. Papers*, vol. 60, no. 7, pp. 1800–1809, Jul. 2013, doi: 10.1109/TCSI.2012.2230494.
[13] S.-H. Moon *et al.*, "Highly robust integrated gate-driver for in-cell touch TFT-LCD driven in time division driving method," *IEEE J. Display Technol.*, vol. 12, no. 5, pp. 435–441, May 2016, doi: 10.1109/JDT.2015.2495121.
[14] W. J. Chew, Y. H. Tai, C. H. Lin, and P. H. Hsiao, "49-3: In-cell active touch circuit using a-Si TFT for large size panel," *Soc. Inf. Display*, vol. 48, no. 1, pp. 738–741, May 2017, doi: 10.1002/sdtp.11753.
[15] X. Li, D. Geng, M. Mativenga, and J. Jang, "High-speed dual-gate a-IGZO TFT-based circuits with top-gate offset structure," *IEEE Electron Device Lett.*, vol. 35, no. 4, pp. 461–463, Apr. 2014, doi: 10.1109/LED.2014.2305665.
[16] S. Lee, M. Mativenga, and J. Jang, "Removal of negative-bias-illumination-stress instability in amorphous-InGaZnO thin-film transistors by top-gate offset structure," *IEEE Electron Device Lett.*, vol. 35, no. 9, pp. 930–932, Sep. 2014, doi: 10.1109/LED.2014.2333014.
[17] S. H. Ryu, Y. C. Park, M. Mativenga, D. H. Kang, and J. Jang, "Amorphous-InGaZnO4 thin-film transistors with damage-free back channel wet-etch process," *ECS Solid State Lett.*, vol. 1, no. 2, pp. 17–19, Jul. 2012, doi: 10.1149/2.004202ssl.
[18] D. Geng, D. H. Kang, M. J. Seok, M. Mativenga, and J. Jang, "High-speed and low-voltage-driven shift register with self-aligned coplanar a-IGZO TFTs," *IEEE Electron Device Lett.*, vol. 33, no. 7, pp. 1012–1014, Jul. 2012, doi: 10.1109/LED.2012.2194133.
[19] D. Geng, Y. F. Chen, M. Mativenga, and J. Jang, "Touch sensor array with integrated drivers and comparator using a-IGZO TFTs," *IEEE Electron Device Lett.*, vol. 38, no. 3, pp. 391–394, Mar. 2017, doi: 10.1109/LED.2017.2661405.

YUANFENG CHEN received the M.S. degree in information display from Kyung Hee University, Seoul, South Korea, in 2015, where he is currently pursuing the Ph.D. degree. His current research interests include design of oxide and LTPS TFT-based circuits for display and sensor applications.

DI GENG received the Ph.D. degree in information display from Kyung Hee University, Seoul, South Korea, in 2017. He is currently an Assistant Professor with the Institute of Microelectronics, Chinese Academy of Sciences, Beijing, China. His current research interests include design and fabrication of robust flexible TFT circuits for flexible display and sensor applications.

JIN JANG is a Professor with the Department of Information Display, Kyung Hee University. His current research programs are in oxide and LTPS TFTs for displays, TFT circuits and TFT application to sensors, QLED and flexible AMOLED. He has authored or co-authored over 900 technical publications of which over 560 are in SCI Journals such as *Nature*, *Advanced Materials*, *Advanced Functional Materials*, *Advanced Energy Materials*, *Energy Environmental Science*, *APL*, the IEEE TRANSACTIONS ON ELECTRON DEVICES, and the IEEE ELECTRON DEVICE LETTERS. He is currently the Director of Advanced Display Research Center.