# Design and Implementation of Readout Circuit with Threshold Voltage Compensation on Glass Substrate for Touch Panel Applications



2011 Jpn. J. Appl. Phys. 50 03CC07

(http://iopscience.iop.org/1347-4065/50/3S/03CC07)

Japanese Journal of Applied Physics 50 (2011) 03CC07 **REGULAR PAPER**
DOI: 10.1143/JJAP.50.03CC07

# Design and Implementation of Readout Circuit with Threshold Voltage Compensation on Glass Substrate for Touch Panel Applications

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Received July 8, 2010; accepted November 5, 2010; published online March 22, 2011

A new on-panel readout circuit with threshold voltage compensation for capacitive sensor in low temperature polycrystalline silicon (poly-Si) thin-film transistor (LTPS-TFT) process has been proposed. In order to compensate the threshold voltage variation from LTPS process variation, the proposed readout circuit applies a novel compensation approach with switch capacitor technique. In addition, a 4-bit analog-to-digital converter (ADC) is added to identify different sensed capacitor values and further enhances the overall resolution of touch panel.


## 1. Introduction

Low temperature polycrystalline silicon (poly-Si) thin-film transistors (LTPS-TFTs) have been widely applied in the active-matrix liquid crystal display (AMLCD) for integration of analog and digital circuits on glass. Through LTPS-TFTs process, the circuits fabricated in complementary metal–oxide–semiconductor (CMOS) process like driving circuits, analog-to-digital converters (ADC), timing controller etc. on the peripheral area of display can be integrated on glass substrate to achieve slim, compact, and high-resolution display. The characteristics of poly-Si TFT, such as high carrier mobility, low threshold voltage, high stability, and high reliability, are required to fulfill the SOP application.[1,2)]

Nowadays, touch panel becomes more and more popular for its simplicity and direct interaction with portable products such as satellite navigation devices, mobile phone, personal digital assistants (PDAs), notebook, and so on. Therefore, integrating touch sensing function into glass substrate has attracted much attention in last few years.

Touch panels utilized in electronic consumer products are mainly resistive or capacitive. Resistive touch panel exhibits advantages such as cost-effective, consistent, and durability. On the contrary, disadvantages of resistive-type touch panels include serious glare, low transmittance, and single-touch functionality. Besides, capacitive touch panel can realize multi-touch functionality easily which allows user to operate information instruments more intuitively.[3,4)] In ref. 5, one on-panel readout circuit for touch panel application has been proposed with minimum detectable voltage difference of the proposed circuit is 30 mV. The switch-capacitor (SC) technique is applied to enlarge the voltage difference from the capacitance change of touch panel and the corrected double-sampling (CDS) technique is also employed to reduce the offset owing to process variation.

However, in LTPS-TFTs process, it bases on excimer laser crystallized poly-Si which contributes to random orientation of poly-Si grains, grain size variation, and incomplete termination of grain boundaries. These characteristics usually accompany a random device-to-device threshold voltage variation on panels which result in serious impacts on the accuracy of analog circuits.[6,7)]

In this work, a new readout circuit for capacitive sensor on glass has been designed and verified in 3-μm LTPS process.[8)] The threshold voltage variation can be compensated by employing switch capacitor technique. In addition, it is difficult to integrate a 10- or 12-bit ADC on panel with LTPS process, which is generally utilized in readout circuit for TSP (touch screen panel) application with CMOS process, due to the random device-to-device threshold voltage variation. A 4-bit ADC, which is required by the panel customers, is added on glass substrate with the LTPS process to judge different value of sensed capacitance. In this way, the overall resolution for touch panel can be enhanced by interpolation method.

## 2. Equivalent Model of the Capacitive Sensor Line

A capacitive touch panel utilized in LTPS process consists of an insulator glass, coated with a transparent conductor indium tin oxide (ITO). When the conductive objects such as fingers or metal stylus touch the surface or panel, it induces a small capacitance change on the sensor line and can be regarded as a signal to distinguish whether the panel is touched or not. The equivalent model of the capacitive sensor on the 2.8-in. panel line provided by foundry is shown in Fig. 1 with the total resistance of 150 kΩ and total capacitance of 100 pF. The fanout is the equivalent parasitic resistor and capacitor (RC) of interconnect line between the sensor line to the output node Fin. In order to detect the capacitance change in sensor line, the total sensor line is pre-charged to the supply voltage ($V_{DDA}$). When the conductive objects touch the surface of touch panel, an additional touch capacitance ($C_t$) is formed and connected to the equivalent RC circuit. The charge on sensor line will share charge with $C_t$ and results in a voltage variance on the node Fin. After the charge sharing process, the final value of $V_{Fin}$ can be expressed as

$$V_{Fin} = \frac{C_{total}}{C_{total} + C_t} \times V_{DDA}, \quad (1)$$

where $C_{total} = 100\,pF$ and $V_{DDA} = 15\,V$.

Because the value of $C_t$ is around few pF under different touch area, it contributes to a voltage change from ten to hundred mV under $V_{DDA} = 15\,V$ on the sensor line. The readout circuit is required to amplify the small voltage change for the detection of touch event. Furthermore, the value of $C_t$ is dependent on the distance between touch

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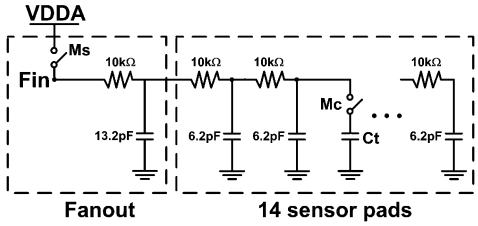



**Fig. 1.** Equivalent model of the capacitive sensor line on a 2.8-in. touch panel.

position and sensor line. Since different $C_t$ leads to different $V_{Fin}$, if the value of $C_t$ can be known, interpolation method can be applied to calculate the touch position when the conductive object touches the position between two sensor lines. The proposed readout circuit with 4-bit ADC can distinguish the difference between $C_t$ and further enhances the overall resolution for touch panel.

## 3. New Proposed Readout Circuit for Capacitive Sensor

To compensate the impact of threshold voltage variation, a new readout circuit of capacitive sensor suitable for LTPS process has been proposed. The block diagram of the new proposed readout circuit is shown in Fig. 2 which consists of a transconductance amplifier, current integrator, and a 4-bit ADC.[9]

In the first stage, the input voltage is transformed into the current $I_{int}$ which equals to $V_{Fin} \times G_m$ by the transconductance amplifier ($G_m$ amplifier). Secondly, the current $I_{int}$ is converted into voltage $V_o$ by charging the current integrator. The $V_o$ can be expressed as:

$$V_o = \int K \cdot I_{int}\, dt, \qquad (2)$$

where $K$ is a constant.

Since $I_{int}$ is dependent on $V_{Fin}$ and $V_o$ is proportional to the integration of current $I_{int}$, the voltage change due to touch event will be amplified as time goes by from eq. (2). In addition, with 4-bit ADC, the proposed circuit can judge the different $V_{Fin}$ caused by different touch position.

### 3.1 $G_m$ amplifier and current integrator

Figure 3 shows the new proposed capacitive touch panel readout circuit with its timing chart. The circuit consists of five pTFT devices, one nTFT device and a loading capacitance $C_{out}$. M1–M5 are switches and M6 is responsible for transconducting voltage into current as a $G_m$ amplifier. The timing chart is composed of three periods: (1) compensation period, (2) reset period, and (3) amplification period. In the compensation period, M2, M3, M5, and M6 are switched on. The node $V_a$ is charged by the supply voltage $V_{DDA}$ until M6 is operated in cut-off region. The voltage difference between the source and gate of M6 equals to the threshold voltage of M6 ($V_{th6}$). In the meanwhile, the node $V_c$ is set to the supply voltage $V_{DDA}$. The voltage difference between node $V_a$ and $V_c$ is stored on capacitor $C_1$. In the reset period, M2 and M5 are switched off as well as M1 is switched on. Therefore, the output voltage $V_o$ is discharged to ground by M1 and the node $V_a$ maintains the same voltage ($V_{DDA} - |V_{th6}|$). During the amplification

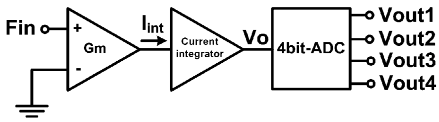



**Fig. 2.** Block diagram of the new proposed capacitive touch panel readout circuit with 4-bit ADC.

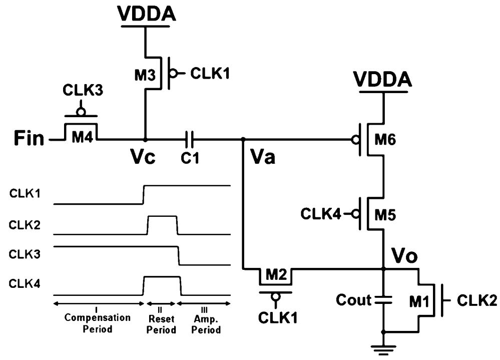



**Fig. 3.** Schematic of proposed readout circuit with threshold voltage compensation and its timing chart.

period, the node Fin is connected to node $V_c$, with a dropping voltage ($\Delta V$) which equals to the voltage difference between $V_{DDA}$ and $V_{Fin}$. Because of the charge conservation at the node $V_a$, the voltage of node $V_a$ also drops $\Delta V$ and equals to ($V_{Fin} - |V_{th6}|$). In addition, node $V_a$ should be discharged to ground every cycle to guarantee that $V_{DDA} - |V_{th6}|$ can be stored at the node $V_a$ successfully. If node $V_a$ is initially larger than $V_{DDA} - |V_{th6}|$, the compensation operation does not work because M6 is turned off.

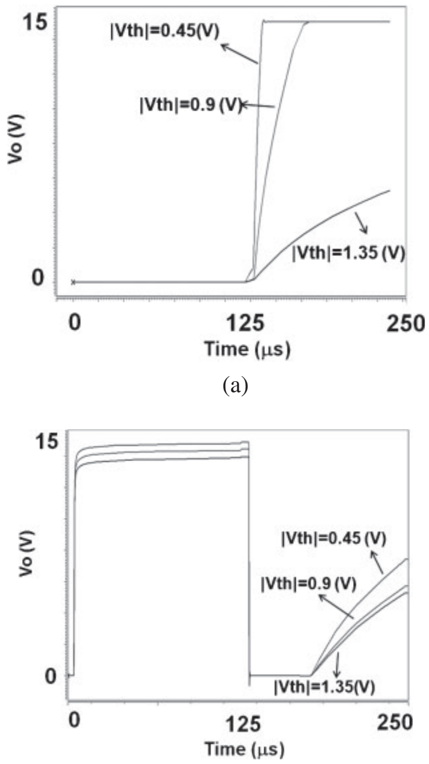
The basic current formula of TFT device can be expressed as follows:

$$I = \frac{W}{2L}\mu_0 C_{ox}(|V_{GS}| - |V_{th}|)^2, \qquad (3)$$

where $\mu_0$ is the carrier mobility, $L$ denotes the effective channel length, $W$ is the effective channel width, $C_{ox}$ is the gate oxide capacitance per unit area, and $V_{th}$ is the threshold voltage of TFT device. The current of M6 in the amplification period is expressed as

$$I_{M6} = \frac{W}{2L}\mu_0 C_{ox}(V_{DDA} - V_{Fin})^2, \qquad (4)$$

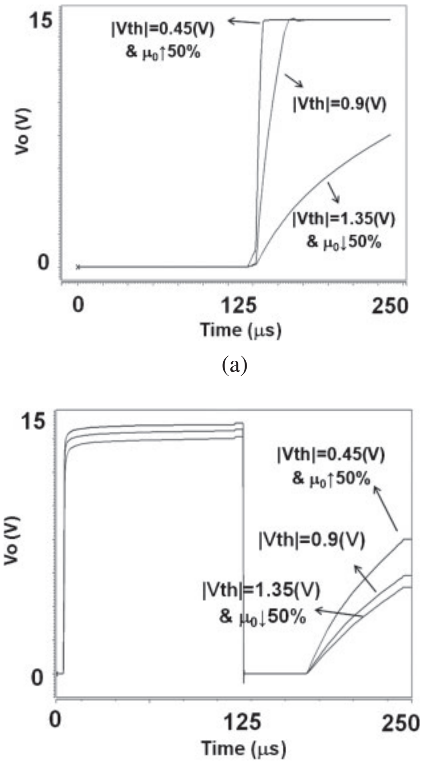
The current in eq. (4) is not relevant to the threshold voltage of TFT device. Using the compensated current to charge the loading capacitor $C_{out}$ can be regarded as current integrator, and the impact of threshold voltage variation on the output voltage $V_o$ can be reduced as shown in Fig. 4. Because the range of threshold voltage variation cannot be provided by the foundry, $\pm 50\%$ threshold voltage variation is applied according to[10,11] in Fig. 4. The difference of output voltage ($V_o$) for the proposed circuit with compensation is much smaller than that without compensation, which means the threshold voltage variation of M6 is successfully compensated. Compared to the readout circuit without threshold voltage compensation, the current $I_{int}$ variation in the amplification period can be reduced from 3120 to 29.3%. In addition to threshold voltage variation, $\pm 50\%$




(a)

(b)

**Fig. 4.** Simulated results of the proposed readout circuit for capacitive sensor (a) without threshold voltage compensation, and (b) with threshold voltage compensation, under different threshold voltages.




(a)

(b)

**Fig. 5.** Simulated results of the proposed readout circuit for capacitive sensor under threshold voltage and mobility ($\mu_0$) variation (a) without threshold voltage compensation, and (b) with threshold voltage compensation.

mobility variation is also simulated in the proposed circuit in Fig. 5. The output voltage $V_o$ of the proposed circuit with mobility variation shows larger difference as compared to that in Fig. 4, and the current $I_{int}$ variation in the amplification period can be reduced from 3550 to 33%.

### 3.2 Analog-to-digital converter

Figure 6 shows the configuration of ADC suitable for LTPS technology.[12,13] The switch capacitor technique is applied to cancel the influence of threshold voltage variation of TFT device. All switches are controlled by the clock signals CLK5 or CLK6. The circuit operation has two steps, (1) storing the logic threshold voltage $V_{th,log}$ on capacitor and (2) compensating $V_{th,log}$ and comparing $V_o$ with the reference voltage. In the first step, CLK6 is set to high and the difference between logic threshold voltage $V_{th,log}$ of inverter and $V_{ref}$ is stored on the capacitor $C_2$. In the second step, CLK6 is switched to low and CLK5 is set to high. Due to charge conservation, the input voltage of inverter becomes $(V_o + V_{th,log} - V_{ref})$. Two inverter stages as buffer are added to guarantee full-swing of the output voltage.

Furthermore, this circuit also has immunity from threshold voltage variation since the $V_{th,log}$ is cancelled by storing itself on $C_2$. Four-bit resolution is achieved by using four same ADC structure with different reference voltages $V_{ref1}$–$V_{ref4}$. Figure 7 shows the simulated result of the proposed circuit under the non-touch event with the digital output code of "1111". Figure 8 shows the simulated results of the proposed readout circuit under different $C_t$. The digital code of ADC presents "1110", "1100", "1000", and "0000" under $C_t = 1$, 2, 3, and $>3$ pF, respectively.

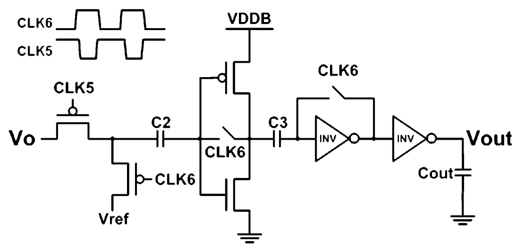



**Fig. 6.** Circuit configuration of ADC.

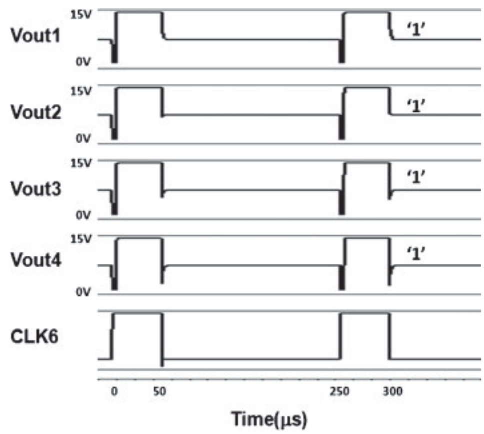



**Fig. 7.** The simulated result of the proposed circuit under the non-touch event with the digital output code of "1111".

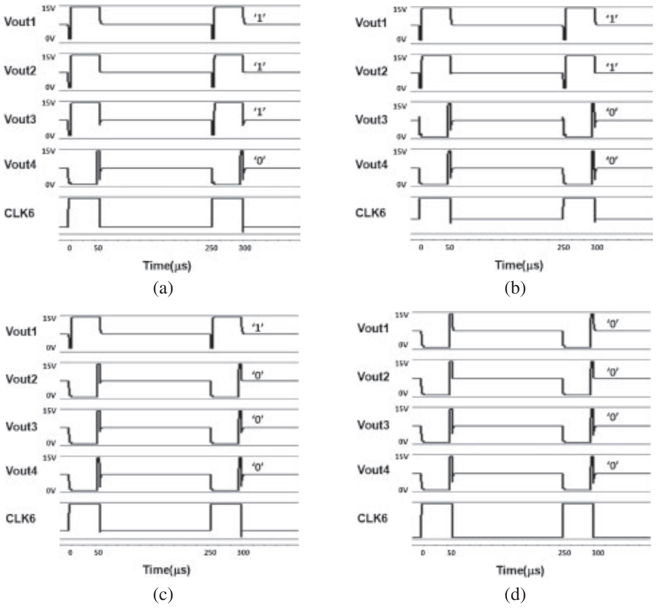



**Fig. 8.** The simulated results of the proposed readout circuit with the $C_t$ of (a) 1 pF (digital output code: "1110"), (b) 2 pF (digital output code: "1100"), (c) 3 pF (digital output code: "1000"), and (d) $C_t > 3$ pF (digital output code: "0000").

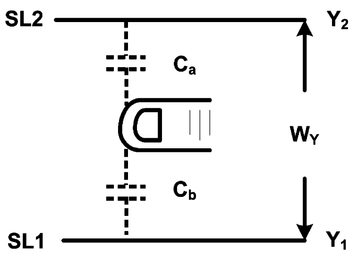



**Fig. 9.** The diagram of panel touched by finger.

According to the digital bits of $V_{out}$, different touch position between two sensor lines can be judged by interpolation method. The maximum operating frequency and the power consumption of the proposed circuit is 5 kHz and 2.34 mW, respectively.

The number of sensor lines for touch panel applications is limited. If the readout circuit can only distinguish whether the panel is touched or not, this kind of circuit cannot judge the correct position but choose one sensor line as the touched side when the area between two sensors lines is touched. If the readout circuit can distinguish the different capacitance value due to different touch area, the interpolation method can be utilized to identify the more accurate position without additional sensor lines and to further enhance the resolution for touch panel applications. The method for extracting touch position is shown in Fig. 9. When the touch position is between two sensor lines, the approximate touch position can be calculated by the following equation:

$$Y_t = Y_1 + \frac{C_a}{C_a + C_b} W_Y, \tag{5}$$

where $Y_t$ is the touch position, $Y_1$ is the position of sensor line 1 (SL1), $C_a$ and $C_b$ are the induced capacitance between touch object and sensor line, and $W_Y$ is the distance between two sensor lines. Since $C_a$ and $C_b$ can be judged by digital codes, more output bits from ADC can gain the higher resolution for touch panel applications.

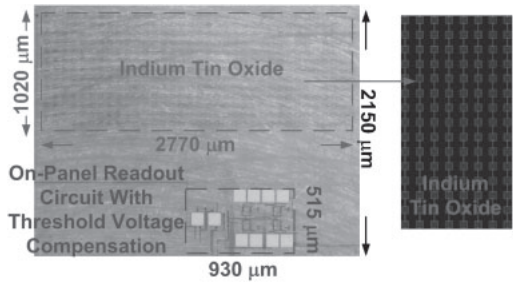



**Fig. 10.** The die photo of the fabricated readout circuit with ITO on glass substrate.

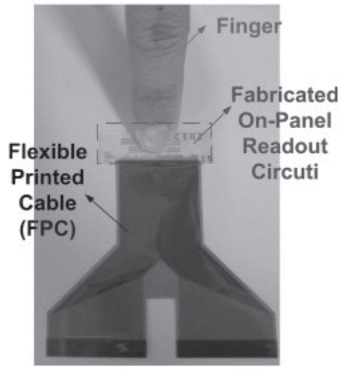



**Fig. 11.** The fabricated circuit on glass substrate to verify the readout function of the proposed circuit.

## 4. Experimental Results

The new proposed circuits have been designed and fabricated in a 3-μm LTPS technology. Figure 10 shows the die photo of the fabricated readout circuit with indium tin oxide (ITO) on glass substrate, where the ITO is utilized to verified the sensor line. When the finger touches the ITO, the touched area between ITO and finger results in capacitance change on the sensor line. The larger area is touched the larger capacitance change on the sensor line. The ITO is drawn with the equivalent resistance of 150 kΩ in the square form instead of a line in Fig. 10 due to the limitation of layout area in the experimental chip. The area of ITO is $1020 \times 2770\,\mu m^2$ and the area of on-panel readout circuit with threshold voltage compensation is $515 \times 930\,\mu m^2$. Figure 11 shows the fabricated circuit on glass substrate to verify the readout function of the proposed circuit, when the ITO on the glass substrate is touched by a finger. The 4-bit digital output codes are utilized to identify the different touch area and to enhance the resolution of the touch panel. The measurement setup is shown in Fig. 12, where the touch capacitance $C_t$ is measured by precision LCR meter of Agilent 4284A, CLK1 to CLK6 are generated by Keithley 4200 dual pulse generator, power supply is GPS 4303 DC power supply, and the output waveforms are observed by SDO603A oscilloscope. Through connecting the two ports of one stand-alone ITO, which is especially designed with the same layout style and layout area to be

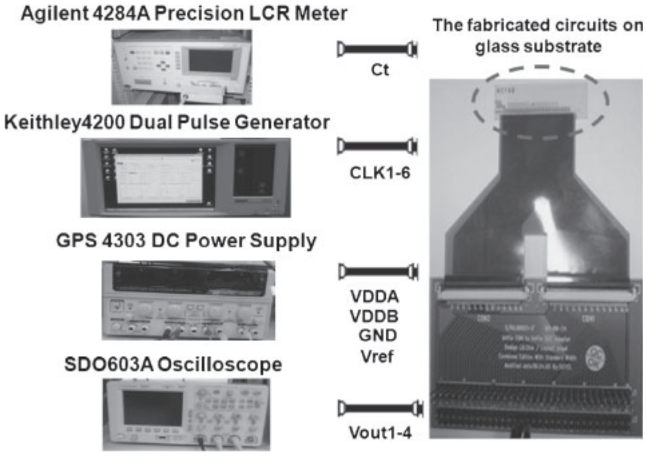



**Fig. 12.** The fabricated circuits on glass substrate to verify the readout function of the proposed circuit and its corresponding measurement setup.

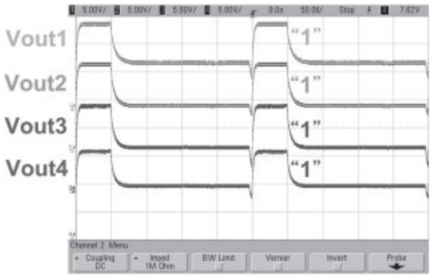



**Fig. 13.** The measured result of the fabricated circuit under non-touch event ($C_t = 0$ pF) with the output code of "1111".

touched for capacitance measurement with Agilent 4284A, the change of capacitance of ITO can be detected. Therefore, the touch capacitance value with different touch area can be also detected.

The fabricated readout circuit is first verified with the externally applied input signals ($V_{Fin}$). Figure 13 shows the measured result of the fabricated circuit under non-touch event ($C_t = 0$ pF), where the digital output code is "1111". Figure 14 shows the measured results of the fabricated circuit under different $C_t$. The digital output code shows "1110", "1100", "1000", and "0000" under $C_t = 1$, 2, 3, and $>3$ pF, respectively. Through the simulation model and devices parameters provided by the foundry, the maximum operating frequency of the proposed circuit can be up to 5 kHz. With device-to-device and glass-to-glass variations in the electrical characteristics of poly-Si TFTs, the operating frequency in the measured results is 4 kHz. However, this is fast enough for touch panel application. In addition, the power consumption is 2.34 mW under 4-kHz operating frequency. After the successful verification of readout function, the fabricated chip is measured by the different touch area of the finger with a 100-pF capacitor connected to the $V_{Fin}$ node, which is used to simulate the touching event modeled in Fig. 1. The different digital output codes are confirmed according to the different touch area of ITO. Figure 15 shows the measured result of the fabricated circuit under non-touch event, where the digital output code is "1111". Figure 16 shows the measured results of the

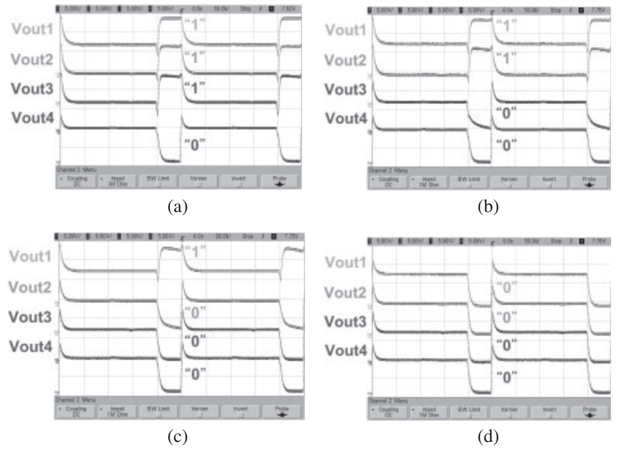



**Fig. 14.** The measured results of the fabricated readout circuit verified with the $C_t$ of (a) 1 pF (digital output code: "1110"), (b) 2 pF (digital output code: "1100"), (c) 3 pF (digital output code: "1000"), and (d) $>3$ pF (digital output code: "0000"). The corresponding digital codes can be successfully generated at the output $V_{out1}$, $V_{out2}$, $V_{out3}$, and $V_{out4}$.

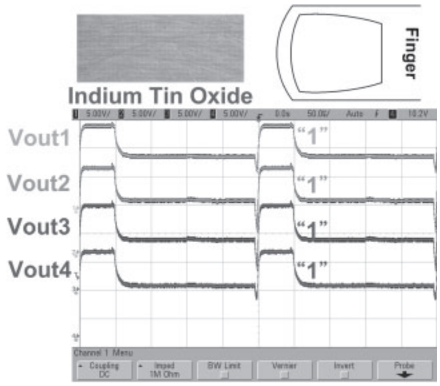



**Fig. 15.** The measured result of the fabricated circuit under non-touch event.

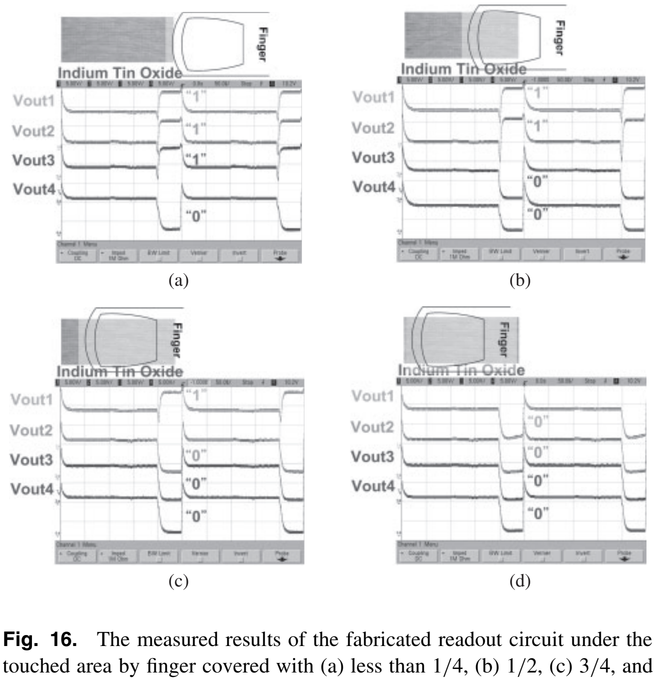



**Fig. 16.** The measured results of the fabricated readout circuit under the touched area by finger covered with (a) less than 1/4, (b) 1/2, (c) 3/4, and (d) full of the ITO area.

fabricated circuit under different touch area. The digital output code shows "1110", "1100", "1000", and "0000" when the touched area by finger is covered with less than 1/4, 1/2, 3/4, and full of the ITO area, respectively. By further analyzing the 4-bit digital codes, the corresponding functions, such as zoom in, zoom out, move, and so on, can be performed on the touch panel by the appropriate algorithm of software in the system.

## 5. Conclusions

An analog readout circuit for capacitive sensor on glass substrate has been successfully designed and fabricated in a 3-μm LTPS technology for panel application. The switch capacitor technique is applied to enlarge the input signal and to eliminate the influence of threshold voltage variation successfully. This new proposed circuit architecture can not only distinguish the panel is touched or not, but also distinguish different value of touch capacitance to further know the touch position between sensor lines.

## Acknowledgement

This work was supported by AU Optronics Corporation, partially supported by the "Aim for the Top University Plan" of National Chiao-Tung University and Ministry of Education Taiwan, R.O.C., and partially supported by National Science Council (NSC), Taiwan, under Contract of NSC 98-2221-E-009-113-MY2.


1) T. Nishibe and H. Nakamura: J. Soc. Inf. Disp. **15** (2007) 151.
2) C.-C. Tsai, M.-D. Ker, Y.-H. Li, C.-H. Kuo, C.-H. Li, Y.-J. Hsieh, and C.-T. Liu: SID Int. Symp. Dig. Tech. Pap. **40** (2009) 1283.
3) C.-H. Li, M.-J. Jou, and Y.-J. Hsieh: Proc. IDW, 2009, p. 2127.
4) E. Kanda, T. Eguchi, Y. Hiyoshi, T. Chino, Y. Tsuchiya, T. Iwashita, T. Ozawa, T. Miyazawa, and T. Matsumoto: SID Int. Symp. Dig. Tech. Pap. **39** (2008) 834.
5) T.-M. Wang, M.-D. Ker, Y.-H. Li, C.-H. Kuo, C.-H. Li, Y.-J. Hsieh, and C.-T. Liu: SID Int. Symp. Dig. Tech. Pap. **41** (2010) 1933.
6) M.-D. Ker, C.-K. Deng, and J.-L. Huang: J. Disp. Technol. **2** (2006) 153.
7) J.-S. Chen and M.-D. Ker: J. Disp. Technol. **3** (2007) 309.
8) Y.-T. Lin, Y.-C. Lin, T.-M. Wang, and M.-D. Ker: Proc. AM-FPD, 2010, p. 121.
9) Y.-S. Tiao, M.-L. Sheu, S.-M. Wu, and H.-M. Yang: Proc. IEEE Electron Devices and Solid-State Circuits, 2005, p. 631.
10) Y.-H. Tai, C.-C. Pai, B.-T. Chen, and H.-C. Cheng: IEEE Electron Device Lett. **26** (2005) 811.
11) S.-H. Jung, W.-J. Nam, and M.-K. Han: IEEE Electron Device Lett. **25** (2004) 690.
12) T. Nakamura, H. Hayashi, M. Yoshida, N. Tada, M. Ishikawa, T. Motai, and T. Nishibe: SID Int. Symp. Dig. Tech. Pap. **36** (2005) 1054.
13) T. Kumamoto, M. Nakaya, H. Honda, S. Asai, Y. Akasaka, and Y. Horiba: IEEE J. Solid-State Circuits **21** (1986) 976.