High Precision Active-Matrix Self-Capacitive Touch Panel Based on Fluorinated ZnO Thin-Film Transistor

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***Abstract*—Matrix-addressed capacitive sensing is popularly employed in advanced multi-touch panels. While the number of simultaneous touch points of a passively addressed matrix is limited, the simultaneous touch points of an actively addressed matrix are constrained only by the size of the matrix and can be more densely packed. Since the touch panel is typically inserted between a display panel and the user, it would be the best if the transistors in an active-matrix touch panel are transparent. Reported presently is such a panel realized using a fluorinated zinc oxide transparent thin-film transistor technology. The technology can be applied to construct panels requiring high touch resolution, such as precision stylus pen-based writing, fingerprint sensing and sensing of the area of the touch, etc.**

***Index Terms*—Multi-touch, thin-film transistor, transparent electronics, zinc oxide.**

I. INTRODUCTION

Nowadays, multi-touch panel is the main-stream interaction technology on mobile applications, such as smart phones and tablet PCs [1]. It allows users to interact with a system through the concurrent use of several points of touch and permits multiple users to work or play together. There are several approaches to realize this technology, e.g. resistive, surface acoustic wave, infrared, camera, projected capacitive, electromagnetic resonance and so on [2, 3]. Among these, the projected capacitive touch is widely used due to its relatively low cost, high sensitivity, non-surface-active, high portability and high optical transmittance [2, 4, 5].

However, the conventional projected capacitive touch array is passive-matrix (PM). Similar to the passive-matrix flat panel display, it is difficult to enhance the resolution due to the soaring parasitical and coupling capacitance as the touch element scales down. The popular used size of each touch element of projected capacitive touch panel is about 5mm×5mm. If the size of the element is reduced to less than 1mm×1mm, a human finger will cover dozens of touch elements, forming large capacitance and shunting more charges. As a result, the capacitance detection circuits will be unable to distinguish the scanning line being touched or not. With the low resolution, the projected capacitive touch panel cannot recognize the fine stylus input, which does not meet the people's growing demand for high precision input. In order to obtain both the high precision input and multi-touch functions, different touch techniques are combined in one panel, such as the projected capacitive multi-touch panel integrated with the electron magnetic resonance handwriting technology. However, the electron magnetic pen cannot realize the real-time handwriting with different painting area of stroke. Moreover, this two-in-one touch panel increases the cost and thickness, and is also not compatible with the displays' process.

In this paper, we propose an active-matrix (AM) self-capacitive touch panel. Similar to the active-matrix flat panel display [6], it is easy to achieve high resolution due to the control of each element by a thin film transistor (TFT). This TFT using fluorinated zinc oxide (F-ZnO) as an active layer has high electrical performance, low process temperature and high transmittance [7]. The self-capacitor in each element of the proposed touch panel can be switched on or off easily by the F-ZnO TFT, resulting in lower parasitical capacitance and hence higher resolution. As a result, higher precision touch panels with touch element size of 1mm×1mm can be realized. It allows the use of capacitive pens with fine nibs for handwriting input and also the use of fingers for multi-touch interaction, and hence can be applied to electronic commercial digital signature, art designing, office drawing and so on. This novel transparent touch panel is fabricated on glass which is to be placed on displays. With improvements to the process and structure, this can be implemented as in-cell or on-cell touch-screens [4, 8]. Thus, the active-matrix self-capacitive touch technique would be a promising candidate for the next generation high precision touch sensing technology.

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II. Work Principle Of PM And AM Touch Panel

There are two sensing methods of the PM projected capacitive touch panel: self-capacitive and mutual capacitive methods. Though the self-capacitive touch panel has high touch sensitivity, it is less used in mobile devices. Since the self-capacitive touch panel is subjected to ghost effect, it is not suited for multi-touch applications [9]. The popular multi-touch panel uses mutual capacitive sensing method with the working principle as shown in Fig.1 [10]. An excitation signal is applied to the horizontal driving line and transfers to the vertical sensing line through the mutual capacitance. If a finger touches the intersection of the two lines, the final sensed mutual capacitance reduces due to the current division of the finger [2].

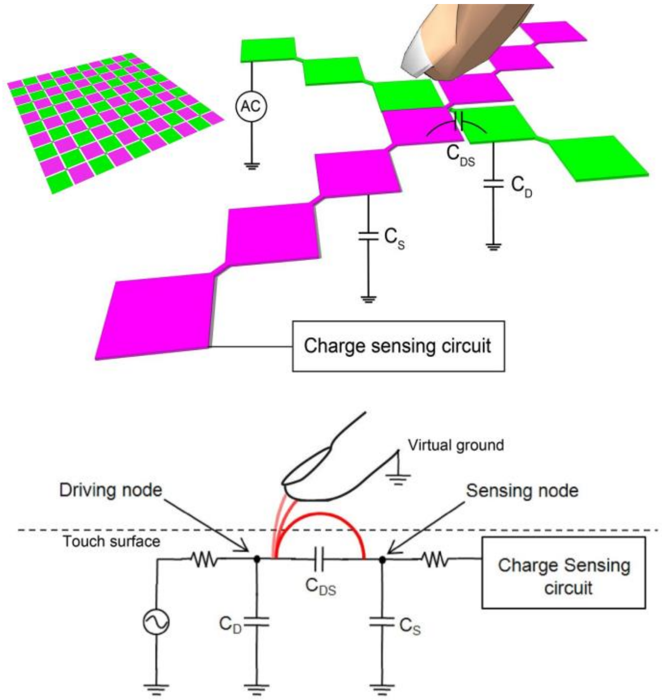

Fig. 1. Schematic diagram and equivalent circuit of mutual capacitive touch sensors when one point was touched.

Several techniques were proposed to detect the capacitance variation for the PM capacitive touch panel, such as successive approximation, relation oscillator and RC delay algorithm. Here we built a Capacitive Voltage Sensing model to analyze the detection sensitivity as shown in Fig. 2a. An input sinusoidal signal, V_{in}, is applied through a coupling capacitor, C_{DS}, over the driving and sensing node to the capacitive sensing circuit. A sensing parasitic capacitor, C_S, is used to represent the parasitic capacitor of each cross node of the driving and sensing line. If the cross node is touched, a parasitic capacitor to virtual ground, C_{SF}, is made, forming a capacitive voltage divider. Fig. 2b shows the simplified circuit of the PM touch model. The variable capacitance, ΔC_{DS}, denotes the change of C_{DS} with/without touching. The output voltage, V_{out}, is continuously acquired by an ADC and demodulated synchronously with V_{in}. According to the voltage divider rule, ΔV_{out} can be estimated by:

$$\Delta V_{out}=\left(\frac{C_{DS}}{C_{DS}+m\times C_S+n\times C_{SF}}-\frac{C'_{DS}}{C'_{DS}+m\times C_S+n\times C_{SF}}\right)V_{in} \tag{1}$$

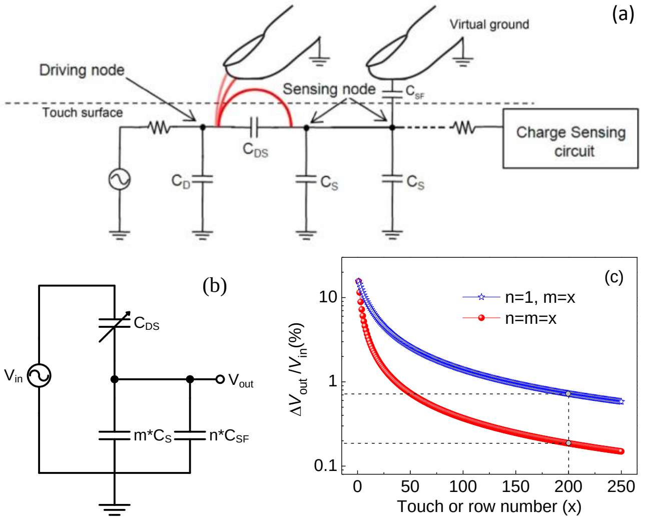

Fig. 2. (a) Schematic diagram and (b) equivalent circuit of mutual capacitive touch sensors when multi points were touched. (c) The dependence of $\Delta V_{out}/V_{in}$ on the row number or the touch points at one sensing line.

$$\Delta C_{DS}=C_{DS}-C'_{DS} \tag{2}$$

Where C'_{DS} is the coupling capacitor when the scanning cross node is touched, m the number of driving row, and n the number of touch points. Assuming that the change of coupling capacitance ΔC_{DS} is about 50%C_{DS}, C_{DS} of 150fF, C_S of 50fF, and C_{SF} of 150fF, the relationship of the touch sensitivity (defined as $\Delta V_{out}/V_{in}$) and the row or touch number is shown in Fig. 2c. If only one point is touched (n=1), the sensitivity decreases with the increase of row number [10, 11]. At the row number of 200, the touch sensitivity is only 0.72%, which is ~14 times smaller than that at the row number of 10. Thus, the application of this method in high resolution or large area touch screens is limited. It is noted that with the increase of the simultaneous touch points on one sensing line, the touch sensitivity of one point decreases rapidly. For example, when 200 points are touched, the $\Delta V_{out}/V_{in}$ is only 0.18%, which is up to 100 times smaller than that of only one point touched. Obviously, this projected capacitive method is not suitable for true multi-touch applications as multiple touches will cover many touch points and reduce sensitivity dramatically.

An active-matrix (AM) capacitance multi-touch system which combines both self-capacitive sensing and the use of transparent F-ZnO TFTs is presently proposed to obtain high precision and high touch sensitivity touch experience. The F-ZnO TFT is scanned to switch off/on each capacitive electrode pad and hence reduces the effective parasitic capacitance, which can precisely recognize each touch point. The size of the capacitive pitch as small as 1mm by 1mm can be achieved. Therefore, this high resolution multi-touch system can simultaneously realize two functions: capacitive multi-touch and high precise handwriting input.

The AM touch panel works on the principle of self-capacitive sensing. A block of a 2-D scanning array is shown in Fig. 3a. Each touch element consists of a self-capacitor electrode, connected to one source (or drain) electrode of an F-ZnO TFT. The other drain (or source) electrode links the sensing column to capacitance detection

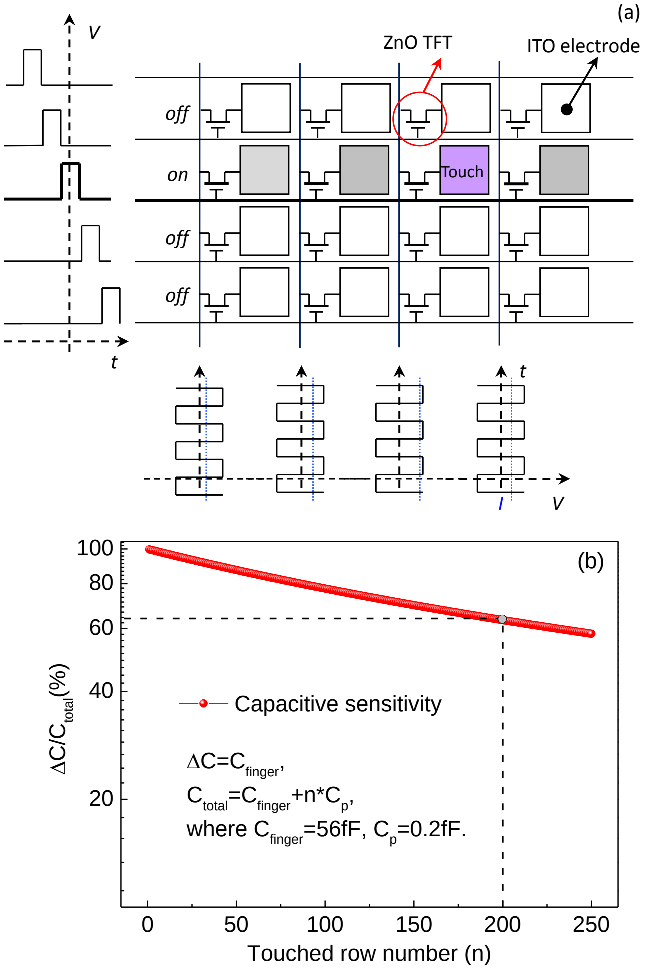

Fig. 3. (a) Schematic structure and working principle of the active-matrix self-capacitive touch panel, and (b) the dependence of $\Delta C/C_{total}$ on the touched row number at one sensing column.

circuits. The voltage scanning row connects the gate electrode to control the on/off state of the TFT. When a finger or capacitive pen touches on the backside of the glass, a capacitor (C_{finger}) is formed between the electrode and the finger which acts as the virtual ground. This capacitor is sensed by an output AC signal through the on-switch transistor when a scanning voltage pulse is applied to the corresponding row (see the black thick line of Fig. 3a). In Fig. 3a, the purple and gray ITO electrodes represent the touched center and around elements at the scanning row, respectively. While the TFTs in other rows are all switched off, their corresponding self-capacitors cannot be sensed. Thus the crosstalk coupling capacitance is very small, even when several points on the same column are touched. By simple calculation, Fig. 3b reveals the relationship of the capacitive sensitivity and the touched row number on the same sensing column. It is found that even when there are 200 touched points, the touch sensitivity just drops 38% compared to that when there's only one touched point. Therefore, the AM touch panel is easier than the PM touch panel to achieve high resolution touch experience.

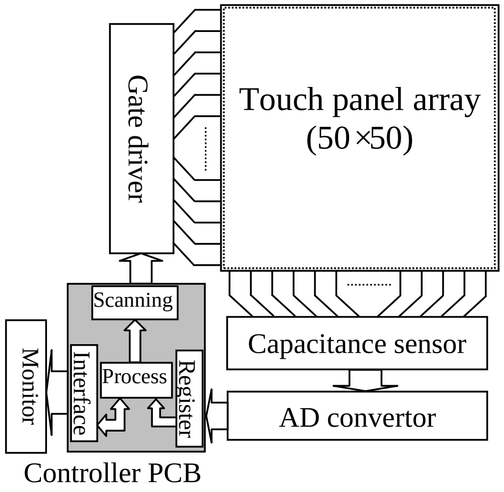

Fig. 4. Block diagram of the architecture of the whole AM touch system circuits, including gate driver, capacitance sensor and microcontroller.

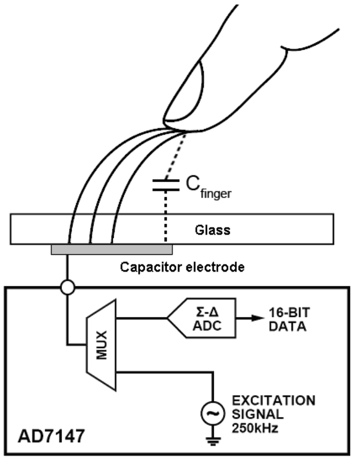

Fig. 5. Schematic diagram of the self-capacitive sensing circuit (cited from ADI manual).

III. PERIPHERAL CIRCUIT OF AM TOUCH PANEL

Fig. 4 shows a block diagram of the whole AM touch system. The system consists of microcontroller, capacitance detecting and conversion circuit, scanning voltage driver and the glass panel of AM touch array. The microcontroller informs the gate voltage driver to scan the row and records the corresponding row number. Meanwhile the microcontroller receives the converted capacitive digital data of each column from the sensing circuit and then transfers these data together with position information (row and column number) to PC for process and display.

Fig. 5 shows how the capacitor sensing IC AD7147 from Analog Devices Inc. measures capacitance change for self-capacitive sensor. The sensor electrode on the panel comprises one plate of the capacitor C_{finger}. The other plate of C_{finger} is the user's finger, which is grounded with respect to the sensor input. At first, the AD7147 outputs an excitation signal to charge the capacitor of the plate. The square wave excitation signal with 250kHz is applied to the sensing line, and then the modulator continuously samples the charge passing through the sensing line. The charges are converted to 16-bit digital data via a digital filter. Finally the resulting digital data is transferred to the microcontroller by I^2C interface for further process.

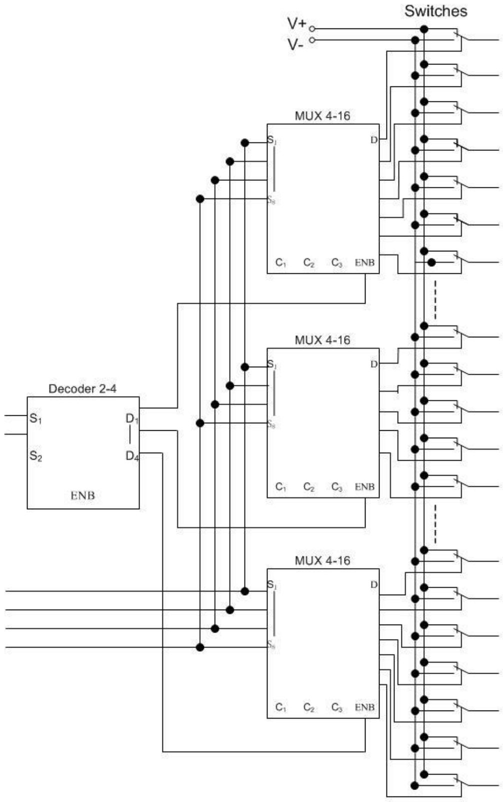

Fig. 6. Gate driver architecture of the AM touch panel.

The gate voltage driver in the presented AM touch panel is based on the single-pole-double-throw analog switch IC MAX333 as shown in Fig. 6. Since the TFTs need ±5V to turn on or off, MAX333 IC was chosen to realize arbitrary value of positive or negative voltage. In order to control the output voltage of every port, three 4-16 multiplexers are combined with one 2-4 decoder to form a switching mechanism using 6-bit control. Thus, 48 switches can be controlled by the input signal, obtaining a set of scanning voltage pulse.

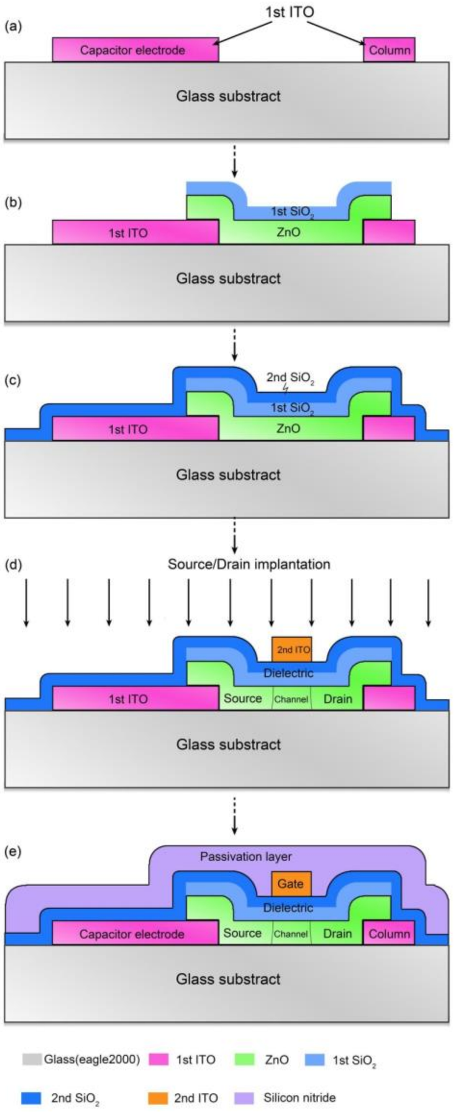

Fig. 7. Schematic diagrams showing the evolution of the device cross-sections during the fabrication of the F-ZnO TFT touch panel.

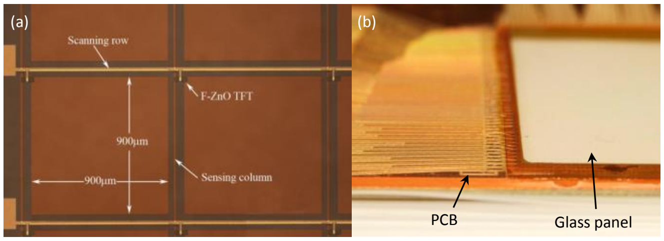

Fig. 8. (a) The optical micrograph of the touch array and (b) the photograph of the wire bonded touch panel on PCB.

IV. PANEL FABRICATION

The touch panel array was fabricated on a 500μm thick glass substrate (eagle 2000). The evolution of the schematic cross section of each element is shown in Fig. 7. The construction of the AM multi-touch panel began with sputtering deposition of 100nm thick ITO conduction layer on glass. This ITO layer was served as the capacitor electrode and sensing column, and patterned by lift-off technique as indicated in Fig.7a. An active layer of ZnO thin film was deposited by radio frequency (RF) magnetron sputtering method in an mixture gas of oxygen (O_2) and argon at a ratio of 1:9, a working pressure of 5mTorr and a RF power density of 6W/cm^2. Then the panel was placed in a plasma-enhanced chemical vapor deposition (PECVD) system and fluorinated in a tetrafluoromethane (CF_4) plasma, with the immersion time of 6mins [12]. A layer of 50nm thick PECVD SiO_2 was deposited at 300^{o}C to form a portion of the gate dielectric. This oxide layer also protected the ZnO from being exposed to ambient O_2 and moisture during the subsequent processes. After the patterning of the active islands in a trifluoromethane (CHF_3)/O_2 plasma and sequentially etched in a 0.1% aqueous hydrofluoric acid solution as indicated in Fig.7b, a second 50nm thick SiO_2 layer forming the remaining portion of the gate dielectric layer was deposited as indicated in Fig.7c. A second 130nm thick indium-tin oxide (ITO) gate electrode was sputter-deposited and patterned to obtain the gate electrode and voltage driving row. Using 135KeV BF_2^+ at a dose of 5×10^{15}/cm^2 as the dopant species, boron (B) [13] and F were implanted into the source/drain regions as indicated in Fig.7d. A 400nm thick sputtered passivation layers was

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deposited on the panel as indicated in Fig.7e. After contact holes were opened, aluminum was deposited and patterned to form the metal pads connected to column (1st) and row (2nd) ITO lines. After slicing the square panel, wire bonding was used to connect the driving and sensing circuit PCB to these metal pads. Fig. 8a and 8b exhibit the micrograph of the fabricated AM touch structure and the photograph of the bonded touch panel to PCB, respectively.

V. RESULTS AND DISCUSSION

Typical transfer characteristics of the plasma fluorinated ZnO TFTs on glass substrate are shown in Fig. 9a. The channel width and length of the TFT device are about 30μm and 10μm, respectively. Plasma fluorinated ZnO TFT used in this system is not only due to its transparent property but also its high mobility, low cost, good uniformity and high reliability compared to other amorphous metal oxide semiconductor devices. The introduction of fluorine effectively makes up the deficiency of the polycrystalline pure ZnO TFT, since fluorine immersed in ZnO can passivate its native defects and grain boundary. The detailed process and explanation of F-ZnO TFT can be found in Ref. [7, 12]. For the present tests of the F-ZnO TFT made in the same process of the touch panel, a linearly extrapolated threshold voltage of ~1.6V, an *SS* of ~0.28V/decade, an on/off current ratio of $\sim 5\times10^{7}$ and a field-effect mobility of ~70cm^2/Vs can be extracted from the dependence of I_D on V_{GS} in the saturation regime. The S/D regions are connected to the first ITO layer with a specific contact resistance of 0.25Ω-cm^2 (see the contact IV in Fig. 9b), indicating the acceptable Ohmic contact for small parasitical resistance. High insulating ability between the two ITO layers was examined through the low leakage current testing as shown in Fig. 9c. The photo sensitivity or stability of the F-ZnO TFT is an important property for the application of the touch panel, and it was measured in our previous paper [14]. Even exposed to white light of ~2000lm, the *IV* behavior of the F-ZnO TFT is still the same as that measured in dark ambient. Therefore, the TFT is fit to put on the glowing displays.

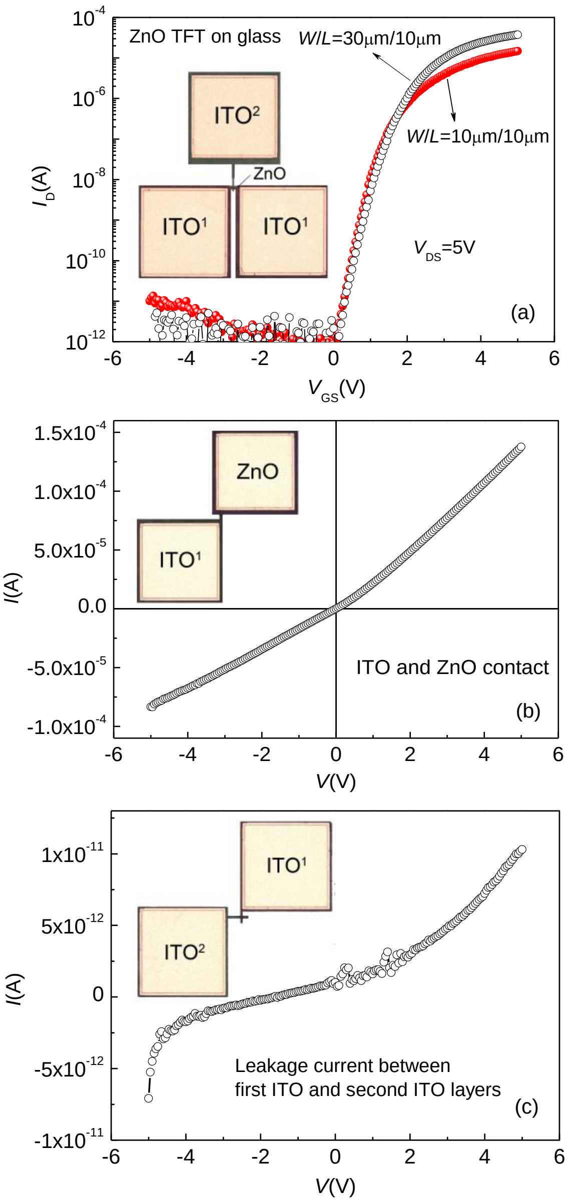


Fig. 9. (a) Typical transfer characteristics of F-ZnO TFTs formed on glass, (b) the contact *IV* between first ITO layer and ZnO S/D regions, and (c) the leakage current between first ITO and second ITO layer.

In order to make sure the TFT devices can switch on or off the high frequency signal, a simple circuit mode was built to test its high frequency response as shown in Fig. 10a. For this case, one single F-ZnO TFT is connected directly to a capacitor sensor AD7147 and a small capacitor. Switch S1 and S2 inserted here are respectively used to control the TFT and simulate the finger touch. A 250kHz AC signal from AD7147 was applied to the drain terminal and a 1pF capacitor was connected to the source terminal of the ZnO TFT. If the transistor is turned off (open switch S1), the change of the capacitance digital data read from AD7147 is very small when switching S2 from on to off or reverse. Whereas when the transistor is turned on (close switch S1), the capacitance digital code increases rapidly for S2 switching from off to on state, and is ~75times larger than that of the off-state transistor (Fig. 10b), indicating that the F-ZnO TFT can effectively turn off or on the sensing AC signal.

The present AM touch panel consists of an array of 50×50 elements at a pitch of 1mm, and a fingerprint with element size of 100μm×100μm was fabricated at the same time. In theory, the element size can be made as small as 60μm×60μm, which is the standard size of the high precision commercial fingerprint

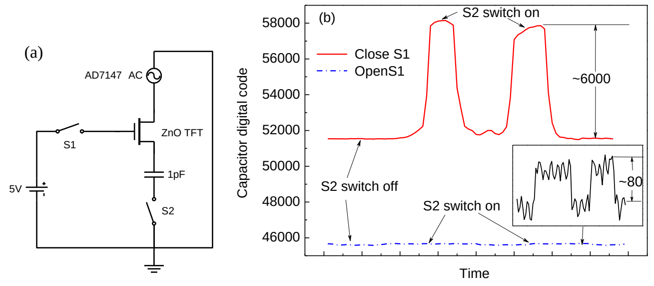


Fig. 10. Single F-ZnO TFT testing (a) circuit and (b) results for self-capacitive sensing IC AD7147.

TABLE I
SPECIFICATION OF THE AM TOUCH PANEL AND THE FINGERPRINT SCANNER

	AM Multi-Touch	**Fingerprint**
Hardware resolution (Array Size)	50 × 50	200 × 200
Pixel size (Accuracy)	1mm × 1mm	100μm × 100μm
TFT size	30μm/10μm	10μm/10μm
Self capacitive electrode size	900μm × 900μm	80μm × 80μm
Panel thickness	500μm	
Touch methods	Finger, stylus	Finger
Operation voltage	±5V	
Interface	Serial, USB	
Controller	AT8052 with custom-made system	

[15, 16]. In this paper, we focus on the study of the high precision touch panel, while the fingerprint scanning needs further investigation since it requires more capacitor sensing and gate driver circuits [17]. Their specifications of the panel are listed in Table I. The touch panel was fabricated on one side of the glass, while the finger touches the other side of the glass. The 500μm thick glass was used as the dielectric of the capacitor and also the protection layer of the whole panel. By using the equation $C=\frac{\varepsilon_0\varepsilon_r S}{t}$, where ε_r=3.9, S=900μm^2 and t=500μm, the finger touch capacitance value of 56fF is obtained. The photograph of the fabricated transparent AM touch panel on a white printed paper is shown in Fig. 11a. It can be seen that the whole panel is transparent enough, and the text or patterns under the glass panel seems clear. In the optical measurement, the transmittance of all stacked layers, including ITO, ZnO, SiO_2 and passivation layers, is over 80% (not shown in this paper). The AM multi-touch system was assembled with three pieces of PCB: controller, gate driver and sensing circuit (see in Fig. 11b). Controller board consists of the power circuit, USB communication chip, and microcontroller AT8052, controlling the gate voltage scanning and receiving the capacitive digital signal. Gate driver board contains 12 pieces of switch chip MAX333, and 3 pieces of multiplexer, outputting 48 ports of gate voltage scanning pulse. Sensing circuit board includes the sensing chip AD7147 and a 5cm×5cm touch glass panel, detecting the touch behavior and transferring the change of capacitance to voltage. Although this system seems too big at the moment, it is a prototype and can be simply integrated into one or two silicon chips with small dimensions.

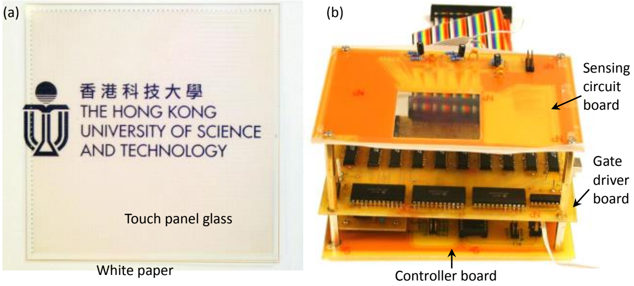


Fig. 11. Photograph of (a) the fabricated AM touch panel on a white paper, and (b) the assembled AM touch system.

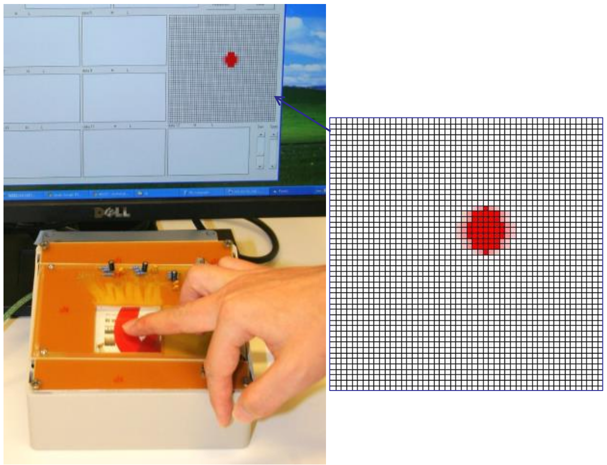


Fig. 12. The AM multi-touch panel prototype detecting one touched finger and displaying the corresponding touch points in monitor.

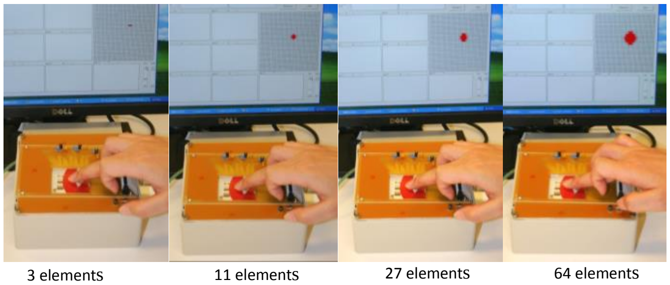


Fig. 13. The AM multi-touch panel detecting the different touch area.

Fig. 12 shows the processed image of touch position when one finger touches the panel. It can be seen that the basic touch function is realized. Compared with the traditional projected capacitive touch panel, the present panel detects more “details” of one finger, i.e., the touch image contains many elements and reveals the shape of the finger with varying touch capacitances of the elements, which is contributed by the high resolution and the low parasitic capacitance of the AM touch structure. By using relevant algorithms, the center coordinate of the image can be calculated to determine the accurate touch point. On the other side, the abundant information of the touch image corresponds to the area of the touch finger, which may be applied for “pressure sensing” [18]. In Fig. 13, if different “pressures” are applied when touching the panel, the number of touched elements for the touch area changed from 3 points to 64 points. This simulated “pressure sensing” has many potential applications, such as playing game in mobile terminal. For example, in racing game, touching the panel with different forces can be used to control the accelerator pedal of a vehicle. This type of experience is currently less adopted for portable devices due to the limitation of touch technology, thus there will be a great market in the future.

Fig. 14 demonstrates a multi-touch zoom gesture with the motion of two touch points. The motion detected and displayed is very smooth and the response time is less than 20ms, which is

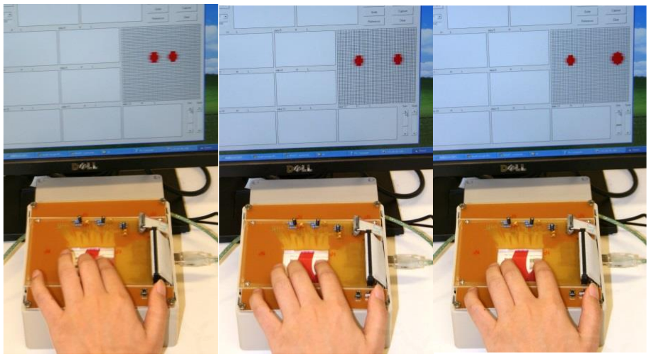


Fig. 14. Demonstration of the motion and scaling functions of the AM touch panel.

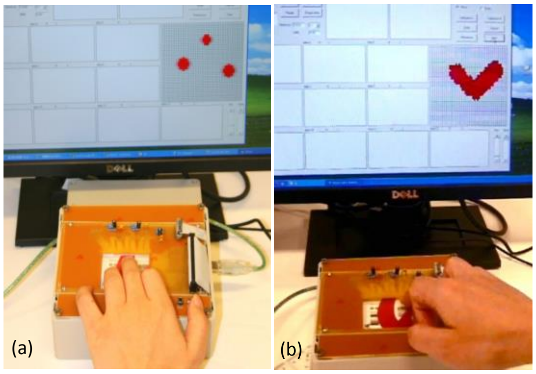
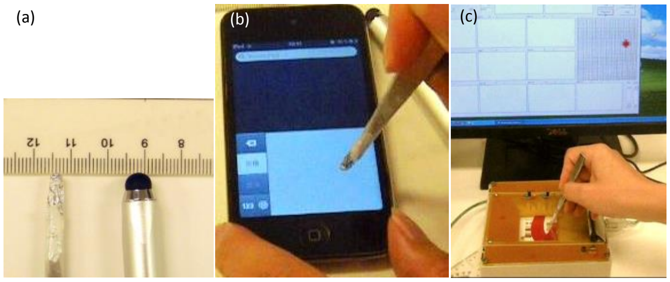


Fig. 15. Demonstration of (a) the Multi-touch and (b) the drawing functions of the AM touch panel.

mostly limited by scanning frequency and communication speed of the microcontroller. The current response speed is sufficient for sliding purposes or multi-touch gestures. Further improvement of the response speed needs a higher speed microprocessor.

The sensitive multi-point touch function of the AM touch panel is shown in Fig. 15a. Three points touch is demonstrated. Actually, nearly infinite points (>2000 points) touch can be detected, realizing true multi-touch. Fig. 15b exhibits the drawing application of the AM touch panel. The software records the track and touched area of the finger, and displays the painting picture. Owing to the high resolution detectable contact area of drawing, various types of professional painting can be realized on the touch panel, for example, oil painting, ink wash painting and so on. The electronic version of these types of painting has many advantages, such as low drawing cost, permanent storage, ease to revise, color and copy. Such electronic painting capability may give rise to a whole new series of applications, leading to a technology revolution.

Fig. 16 illustrates the comparison of the handwriting ability between the conventional projected capacitive touch panel and the present AM touch panel. The nib diameter of the popular capacitive pen is about 5mm with a soft conductive elastomeric to fully contact the panel surface. A handmade stylus with nib diameter of ~2mm was used for comparison purposes as shown in Fig. 16a. There was no problem for both conventional and present touch panel to recognize the input of the large capacitive pen. However, for smaller nib handwriting, the conventional PM capacitive touch panel didn't produce any output as shown in Fig. 16b. Conversely, the present AM touch panel is sensitive to the handmade stylus, detecting a larger touch area than the stylus nib diameter (over 4 red elements as seen in Fig. 16c). In theory, the good working nib diameter of stylus on the present AM touch panel can be smaller than 1mm. If using a capacitive pen with soft tapered tip, one can vary the thickness and style of the stroke to achieve different visual aesthetics. Compared to the conventional PM touch panel, the present AM touch panel has a more complicated structure and fabrication process, as well as a higher cost. However, it has a much higher touch definition, which is suitable for the high precision handwriting. The potential applications of the high precision handwriting of the touch panel include writing commercial signatures, calligraphy, drawing and professional design. It would be possible to develop many practical and fantastic applications if the AM touch panel makes it to the consumer's market.



Stylus size PM touch panel AM touch panel

Fig. 16. Comparison of (a) the small stylus handwriting on (b) the popular passive-matrix mutual capacitive touch panel and (c) the present active-matrix self-capacitive touch panel.

VI. CONCLUSION

A novel active-matrix multi-touch panel based on transparent fluorinated ZnO TFTs has been demonstrated. This panel works on the principle of switched self-capacitive sensing. Compared to the passive-matrix projected capacitive touch panel, the present panel exhibits higher resolution (pixel size is less than 1mm × 1mm) and hence high touch precision due to the high sensitivity of self-capacitive sensing and the small parasitic capacitance. In theory, over 2000 touch points can be detected simultaneously, thus the panel can be applied to precise pen handwriting, touch area sensing, and even fingerprint scanning.

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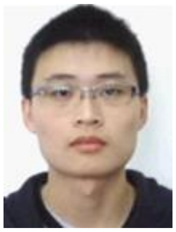

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