On-Display Transparent Half-Diamond Pattern Capacitive Fingerprint Sensor Compatible With AMOLED Display

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***Abstract*— The need for personal security in portable devices has increased. Among several biometric sensing technologies, fingerprint sensing is the most highlighted method. However, a fingerprint sensor in electronics is stifling the demands for a larger interactive display. In this paper, the bottlenecks of placing the sensor on display is discussed, and an on-display mutual capacitive high-resolution transparent fingerprint sensor with a half-diamond pattern is proposed for adapting to the needs of personal security on a larger screen. To overcome various performance limitations on the on-display fingerprint sensor, a metal mesh is used as an electrode material, and the half-diamond pattern is applied. The proposed pattern is compatible with the diamond-patterned active matrix organic light emitter diode display. The proposed sensor has 72 × 72 channels in a 6 mm × 6 mm area. The sensor satisfies the criteria set by the Federal Bureau of Investigation for fingerprint sensing with 322 capacitors per inch, and the measured transmittance in the visible light region is 79.7%. The proposed sensor achieved a capacitance variation 2.3 times larger than that achieved by the conventional sensor. The five-channel fingerprint sensing circuit to examine the feasibility of fingerprint detection is fabricated with the TSMC 0.18-μm process.**

***Index Terms*— On-display sensor, half-diamond pattern, fingerprint sensor, biometric sensor.**

I. Introduction

IN EARLIER days, people used gadgets such as "cellphones" to make phone calls, but now people prefer using "smartphones." A smartphone helps us not only to contact others but also to deal with wider aspects of life by making life more convenient, comfortable, and easy. According to a survey, around 50% of the erstwhile cellphone users are now using smartphones. The survey also estimates that 3 out of 4 cellphone users will use smartphones by 2018. Such a large number of smartphone users will eventually lead to a problem people frequently talk about: Privacy Security. Everyone would have concerns such as – is the smartphone dependable? The smartphone needs the user's authority to access increasingly more personal data to provide better services. Although a passcode is the first step brought to the smartphone to secure private information, it is obvious that people need methods offering better security than a combination of numbers can offer. Biometrics appears to be capable of meeting the requirements of security.

Biometrics usually refers to technologies for measuring and analyzing human body characteristics such as fingerprints, eye retinas and irises, voice patterns, facial patterns, especially those unique to everyone. Therefore, it is the perfect candidate for privacy security. Regarding technical difficulties and cost issues, facial recognition and fingerprint recognition are the only two techniques that has implemented. Google included the facial pattern recognition technology in their flagship smartphone in 2012 [1]. However, facial recognition performs poorly under certain conditions and the sensor has to be held at an angle of less than 20 degrees off in order to function properly. In addition, poor lighting, wearing glasses or sunglasses, long hair, or other objects partially covering the subject's face, low-resolution images, as well as variations in facial expressions result in ineffective recognition. On the other hand, Apple first implemented a fingerprint sensor in their flagship smartphone in 2013 [2], with the sensor capturing a digital image of the fingerprint. Comparably, the fingerprint sensor suffers less from environment conditions than the facial pattern recognition technique does.

Back in the 19th century, fingerprint images were captured by coating the finger with ink and pressing the inked fingers on to papers and cards. Ink-based systems are cumbersome and messy for widespread use. Both, the optical method, using an electronic camera to detect fingerprints, and the ultrasonic method, based on differences in ultrasonic absorption between the ridges and valleys, are proven to be bulky and impossible for use in smartphones. Recently, radio frequency (RF) imaging has been introduced by AuthenTec, and Apple's flagship smartphone [3] has already implemented it. The RF imaging

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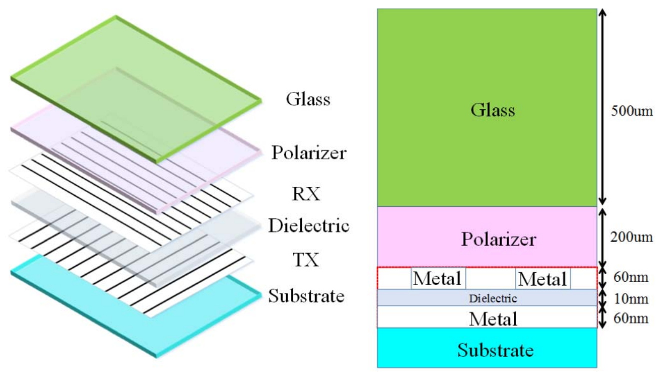

Fig. 1. Layer of conventional mutual capacitive touch screen and dimensions.

technique uses an array of sensors to generate live images of the skin layer's ridge and valley patterns from equipotential contours in the electrical field.

As the need for a larger interactive display grows, the size of the smartphone also increases. This means the display size has the highest priority in a smartphone. Some manufactures have combined the fingerprint sensor and their own activation button, and they have placed it on the front panel of the smartphone. Another solution is to place the sensor on the back of smartphone to have a larger screen area on the front panel, but due to ergonomics, placement on the front panel is more natural when applied to smartphones. A third solution would be to integrate the fingerprint sensors within the display panel. To achieve this, the sensor components have to be transparent and should not interrupt the performance of the display.

In this paper, an on-display transparent capacitive fingerprint sensor is proposed. To improve the sensor performance and avert any degradation of the display, a half-diamond pattern is applied on the proposed sensor. Section II presents information on fingerprints and describes the considerations for designing an on-display fingerprint sensor. A description of the material, the pattern for the proposed fingerprint sensor, and the specifications of the fabricated sensor are discussed in section III. Section IV describes a circuit to verify the fabricated proposed sensor.

II. On-Display Fingerprint Sensor Consideration

Among various types of touch screens, capacitive touch screens are popularly used in mobile devices. There are a self-capacitance type and a mutual capacitance type for the capacitive touch screens. The mutual capacitance type is more widely applicable since the self-capacitance type is weak in resolving position causing the ambiguity in situation of multi-touch. In a mutual capacitance touch screen, there are several layers: the cover glass, the polarizer film, the sensing layer, the dielectric, and the driving layer, which are all shown in Fig. 1. A conventional capacitive touch screen has a perpendicular pattern with sensing, and driving electrodes which are made of indium tin oxide (ITO). A mutual capacitance is created at the intersection of the sensing and the driving electrode. The mutual capacitance is built up of static capacitance, which occurs between the two electrodes and fringing capacitance that occurs at the side of an electrode. The change in the fringing capacitance is used to identify a touch action.

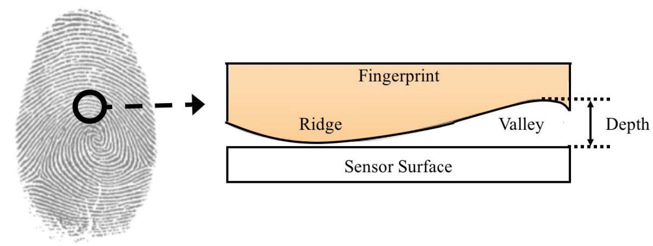

Fig. 2. Shape of fingerprint with ridge and valley.

Since a human body brings fringing capacitance change to the touch-screen panel, the touch action is recognized by sensing variations of the mutual capacitance.

The human skin is classified into two layers: dead dry skin and live skin. Dead dry skin is the outer skin and is considered as dielectric material. Live skin is the inner skin, and is considered as conductive material. When a finger touches the screen panel, the live skin draws the fringing field from the driving electrode, causing a reduction of the effective mutual capacitance. The fringing field is induced between the driving electrode and the sensing electrode. As shown in Fig. 2, the skin at the fingerprint is uneven because of ridges and valleys in the skin. The width of a ridge is around 100 to 400 μm, the depth of a valley from the edge of a ridge is around 60 to 220 μm, and the width of a valley ranges from 75 to 200 μm [4]. A ridge is normally only slightly larger than a valley. The absorbed fringing field from the electrode to the valley is lower than that absorbed from the electrode to the ridge. Therefore, the valley will show a lower capacitance variation than the ridge. By sensing the depth difference from the capacitance difference affected by the fringing field difference, it is possible to distinguish between ridges and valleys.

As shown in Fig. 1, there is a cover glass and a polarizer film above the sensing layer. The cover glass protects the touch screen from damage due to outer elements, and the polarizer film passes only light of certain wavelength to express color. The cover glass in conventional touch screen panels is very thick. The overall thickness of the cover glass and the polarizer film in a conventional smartphone is 700 μm, which is almost 10 times larger than the minimum depth of a valley. As the thickness of the cover glass and the polarizer film is relatively larger than the depth of the valley, difference of the sensed capacitance between ridge and valley become extremely small. In other words, it is vey difficult to differentiate a ridge and a valley. Therefore, the layer over the sensing layer should be thinner than for the conventional type, because capacitance is inversely proportional to the distance between the anode and the cathode plates.

According to the Federal Bureau of Investigation (FBI), an FBI compliant fingerprint sensor should work at higher than 250 dots per inch (DPI) resolution with their algorithm to extract fingerprint pattern from sensors [5]. The specifications of an image-based fingerprint sensor can be applied for capacitive fingerprint sensors as well, because a capacitive sensor can be modeled into capacitors per inch (CPI). Each capacitor in a capacitive sensor is considered as a dot in the optical fingerprint sensor, because sensed data is obtained from the capacitor; hence, a capacitive sensor with more than 250 CPI can detect a fingerprint. Therefore, a mutual capacitive type touch screen with high resolution can be employed as a fingerprint sensor to recognize ridges and valleys.

To satisfy over 250 DPI with a perpendicular pattern, the electrodes have to be narrower and closer. A narrow electrode increases the parasitic resistance leading to an increase of the time constant. In that case, the driving ability of a sensor becomes very low. To scan more than 250 CPI in the same time as a conventional touch screen, the parasitic resistance of the electrode should be small. Therefore, a new material is needed, with a smaller sheet resistance compared to ITO, and which will allow a high frequency signal to drive the high-resolution capacitive sensors on demand.

Additionally, as the electrode becomes narrower, the overlapped areas become smaller than before. It means the mutual capacitance will get smaller as the electrodes become narrower. A general capacitance-sensing block is formed from an inverting operational amplifier with capacitors. By utilizing the ratio of the sensing capacitance to the feedback capacitance, the capacitance variation can be measured. However, there are undesired errors and noise within the sensing block. These are the parasitic capacitances, offsets from fabrication mismatch, noise from transistors, and so on. Furthermore, the environment of the sensor also creates a substantial amount of noise. Therefore, for the capacitive fingerprint sensor to work as a simple sensing mechanism, the sensing capacitance must be large enough to detect accurately regardless of errors and noise.

At present, the proportion of the active matrix organic light emitter diode (AMOLED) used for a mobile display is higher than that of the liquid crystal display (LCD). The advantages of the AMOLED are its fast response time, wide viewing angle, low power consumption, natural color expression, and paper like thickness. However, an RGB pattern cannot be used in a mobile display, because of limitation of the life expectancy of the blue LED in the AMOLED. Therefore, instead of an RGB pattern, a penTile pattern is used for an AMOLED display. Moreover, to realize a high-resolution display of over 400 DPI, a diamond-shaped penTile pattern is used. Within the diamond penTile patterned AMOLED display, the sensing and driving lines in a conventional perpendicular linear patterned touch screen affects the LED pixels negatively. Even though a normal touch screen uses transparent ITO, it reduces the visibility of the display. As a result, new patterns for a fingerprint sensor compatible with the diamond penTile are required to increase the mutual capacitance and enhance the visibility.

III. Proposed on-Display Half-Diamond Patterned Fingerprint Sensor

A. Material

ITO has transparency $>95\%$ and sheet resistance $<100\ \Omega$/sq [6]. The high transparency of the ITO makes it a perfect candidate for an on-display fingerprint sensor, but its sheet resistance is too high. To lower the sheet resistance, a metal mesh is proposed in place of the ITO. Compared to ITO, a metal film has extremely low transparency: 0%.

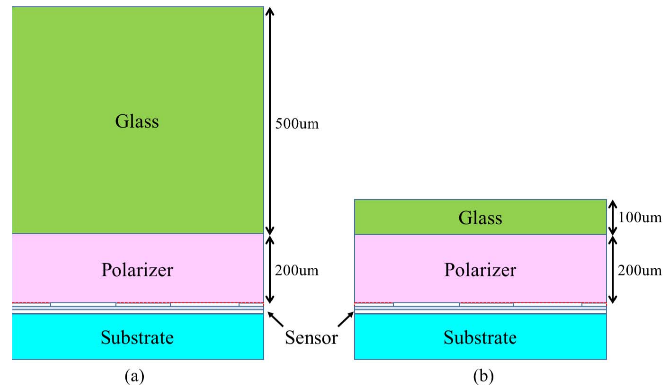

Fig. 3. Comparison between (a) conventional and (b) flexible touch screen layer.

Nevertheless, metal mesh is popularly used in large touch screen panels, such as in TVs, monitors, etc. The metal mesh seems transparent in large panels, because it is extremely narrow compared to the panel. Since an on-display fingerprint sensor must have a very narrow electrode, the metal mesh can be treated as a relatively transparent material. For the proposed on-display fingerprint sensor, Au is used, as its sheet resistance is $2.44\ \times 10^{-8}\Omega$/sq. Therefore, the use of Au electrodes will not affect the speed of the sensor.

Another problem in a fingerprint sensor is the thickness of the cover glass and the polarizer film that takes dominant effect on the mutual capacitance. Since these elements are essential to a display panel, they cannot be removed. Therefore, we propose to use the extremely thin cover glass and polarizer films used in flexible display panels. Conventional cover glass has a thickness of 500 μm, while the polarizer film is 200 μm thick. A cover glass in a flexible display made with plastic is only 100 μm thick, and is 80% thinner than the conventional cover glass. Although a polarizer film in a flexible display has the same thickness as in a conventional one, while adapting it for a flexible display, its thickness is reduced by 60%. A comparison of conventional layers and flexible display layers is shown in Fig. 3. Even though it is still thick for an on-display fingerprint sensor, it can adequately increase the ratio of effective capacitance.

B. Pattern Design

A new pattern is necessary to secure visibility on the diamond penTile pattern AMOLED display, and it must have a higher mutual capacitance than the conventional perpendicular linear pattern. The capacitance between two parallel plates, shown in gray in Fig. 4, is calculated as,

$$C = \varepsilon \frac{wl}{d} \tag{1}$$

where ε is permittivity of the material, w is width of the overlapped area, l is the length of the overlapped area, and d is the distance between the driving and the sensing electrodes, representing the thickness of the dielectric layer. An approximated fringing capacitance at a single edge is,

$$C = \frac{\pi \varepsilon l}{\log\left(\frac{4d}{h}\right)} \tag{2}$$

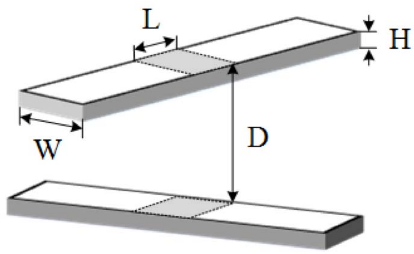

Fig. 4. Two perpendicular electrodes.

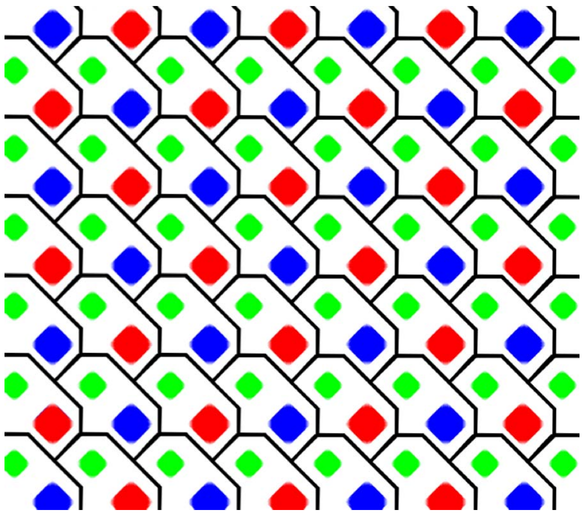

Fig. 5. Half-diamond pattern electrodes on diamond pattern AMOLED display.

where h is the thickness of the electrode [7]. By combining (1), and (2), the approximate total capacitance for two parallel electrodes is achieved. Therefore, the total capacitance in Fig. 4 is

$$C = \varepsilon \frac{wl}{d} + \frac{2\pi\,\varepsilon l}{\log\left(\frac{4d}{h}\right)} \tag{3}$$

Based on (3), to increase the mutual capacitance for accurate sensing, the length of the electrode is modified in the half-diamond style pattern for the high-resolution on-display fingerprint sensor, as treated in section II. The proposed half-diamond pattern compatible with a diamond penTile pattern AMOLED display is shown in Fig. 5.

Since an LED in the display is placed repetitively every 80 μm, the pitch between the electrodes is 75 μm, and the width of an electrode is 5 μm. Therefore, the sensor electrode does not block the LED or degrade the visibility. The designed sensor has 72 $\times$ 72 electrodes or 5,184 capacitor nodes in a 6 mm $\times$ 6 mm area. This translates to 322 CPI, and satisfies the FBI criteria. The length of overlapped area is 24.6 μm.

C. Fabrication

The proposed on-display fingerprint sensor was fabricated at the Ulsan National Institute of Science of Technology Central Research Facilities. The fingerprint sensor is constructed on quartz glass and fabricated using the conventional nanoscale device manufacturing system. The Cr/Au thin-films for the bottom electrode and the Cr/Au and Ti/Au thin-films for the upper electrode are deposited by using the E-beam evaporation technique. Both the bottom and the upper electrodes are patterned by the lift-off technique. The SiO_2 layer, a transparent material, necessary for the insulation of the bottom and the upper electrodes, is deposited by the plasma-enhanced chemical vapor deposition (PECVD) method. The bond pads were passivated by buffered oxide etch (BOE). Fig. 6 shows the patterns in the fabricated sensor and a close-up view of overlapped part of the driving and sensing electrodes with their dimensions.

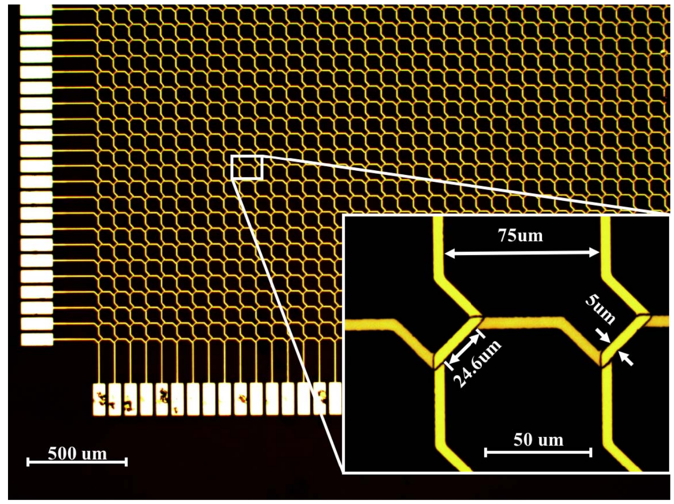

Fig. 6. Photograph of fabricated proposed half-diamond patterns fingerprint sensor and dimensions.

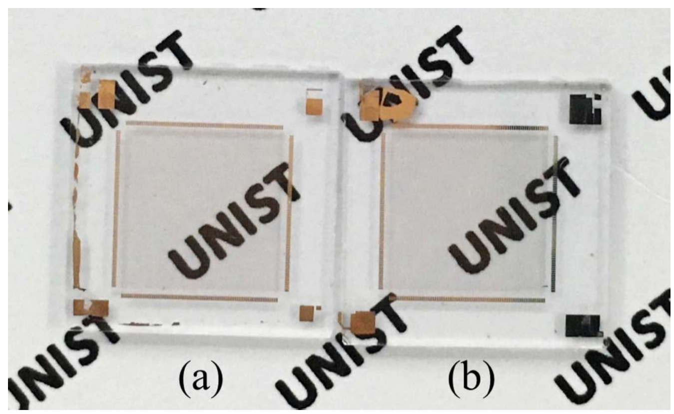

Fig. 7. Photograph of fabricated (a) half-diamond pattern and (b) conventional linear pattern fingerprint sensor in 6 mm $\times$ 6 mm.

D. Sensor Measurement

For comparison, a conventional perpendicular linear pattern is fabricated with the same dimensions as that of the half-diamond pattern. Fig. 7 shows a photograph comparing the transparency between the linear pattern and the half-diamond pattern. Although both sensors are slightly opaque, the letters under the sensors are readable. Fig. 8 shows a measurement of transmittance under a visible ray. A UV/VIS/NIR spectrophotometer, Cary 5000, is used to measure the transmittance of the linear and the half-diamond pattern. For the 500 nm

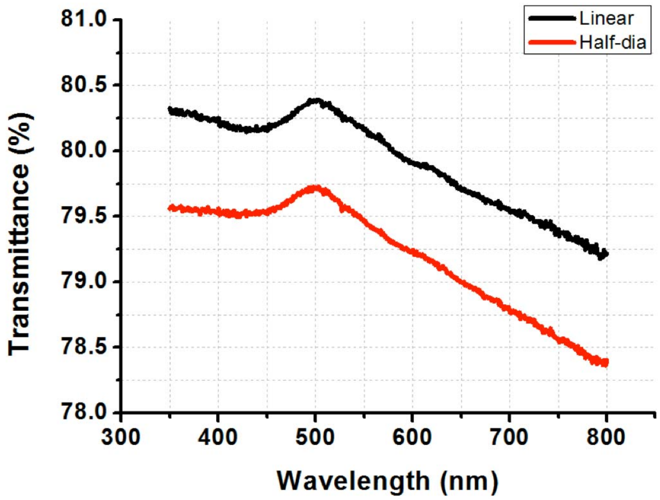

Fig. 8. Transmittance measurement of fabricated linear and half-diamond pattern fingerprint sensor.

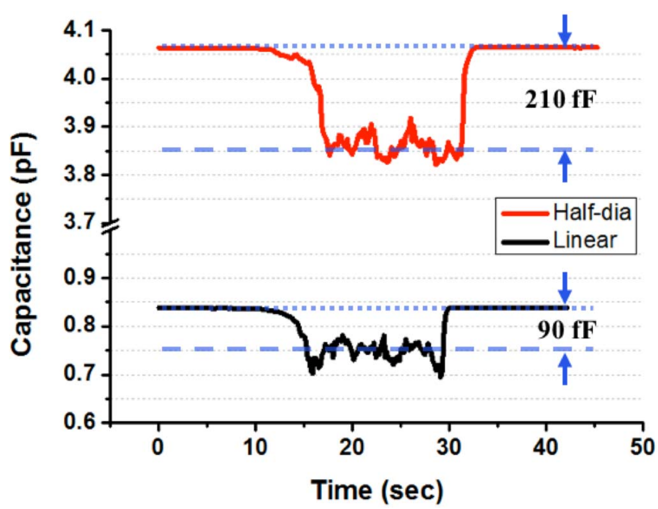

Fig. 9. Capacitance measurement of fabricated half-diamond and linear pattern fingerprint sensor.

wavelength, the transmittance was found to be 80.4%, and 79.7%, respectively. A quartz glass is used as the reference material.

An Agilent E4980A Precision LCR Meter was used to measure the capacitance variations between touch and un-touch conditions in the fabricated sensor by signaling a 1 V AC signal of 1 MHz. The signal was applied to the driving electrode, and the capacitance was measured by reading the signal from the sensing electrode. As it is difficult to place a ridge or a valley accurately on an electrode, un-touch and touch conditions were measured to check the performance. The measurement results of the fabricated sensor are shown in Fig. 9. The dotted and dashed lines in Fig. 9 indicate un-touch and touch conditions, respectively. The linear pattern achieves capacitances of 0.84 pF and 0.75 pF, whereas the half-diamond pattern achieves 4.06 pF and 3.85 pF under the un-touch and touch conditions, respectively. The capacitance variation under the un-touch and touch conditions for the linear and the half-diamond patterns are 90 fF and 210 fF, respectively.

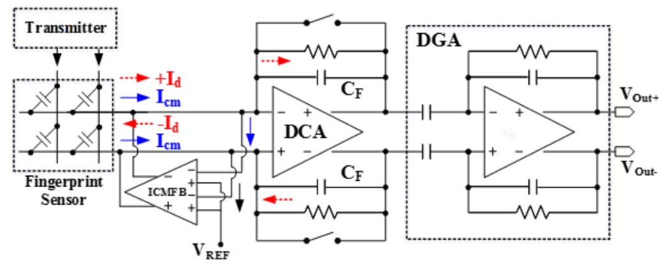

Fig. 10. Block diagram of fingerprint sensor readout circuit.

Therefore, the proposed half-diamond pattern achieves 4.8 times larger static mutual capacitance and 2.3 times larger capacitance variation with the same CPI.

IV. Fingerprint Sensing Circuit

A. Fingerprint Sensor Readout Circuit

Conventionally, systems composed of operational amplifiers are used in the readout circuits of various sensors. A feedback system with an operational amplifier (OPamp) gives stable and accurate results. An inverting amplifier with a feedback capacitor is used for capacitive sensors.

Nowadays, because of their high noise immunity, differential amplifiers are used in readout circuits for sensor applications. Therefore, fully-differential amplifiers are used to test the proposed on-display fingerprint sensor. Fig. 10 shows the circuit used for the measurements [8], [9]. The sensing circuit has a differential charge amplifier (DCA) with input common mode feedback, followed by a differential gain amplifier (DGA). In the differential structure, the common mode is extremely important, because the difference of the common mode levels, known as the offset, can be treated as the fatal noise. Especially in situations where the common mode level is not settled - an example being the touch screen - it is really important to set the common mode levels and make them equal. In the sensing circuit, an input common mode feedback part is made up of a differential difference amplifier (DDA) [10]. In addition, when a differential sensing circuit is present in a touch system, the input differential OPamp receives a large common-mode signal rather than differential signal. If a large common-mode signal flows into a differential OPamp, current steering problems occur, and a possible malfunction may result. Thus, the DDA removes the common-mode signal, shown as a solid arrow in Fig. 10, and transfers only the signal difference, shown as the dashed arrow in Fig. 10. Another essential issue to handle in a touch sensor area is the noise, of which there are three main types: fluorescent noise, charger noise, and display noise [11]–[13]. Since a stable DC supply is used in the test environment, charger noise is not a concern. Furthermore, differential architecture can cancel the display noise because it is a common noise in the touch system. The fluorescent noise is a noise from external light sources. Fluctuations due to fluorescent noise occur when light falls on the touch sensor during touch action. Because light appears as a sine wave, fluorescent noise can be easily canceled by using low pass filters. The DCA works as

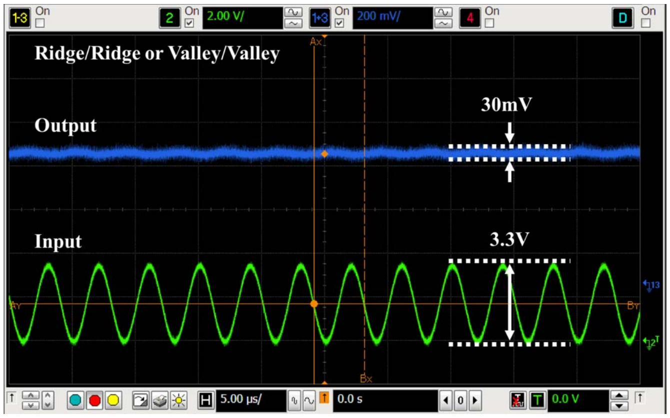

Fig. 11. Measurement result of sensing ridge to ridge, or valley to valley.

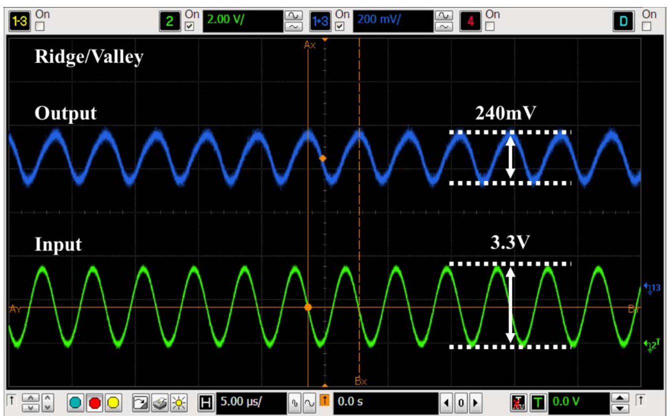

Fig. 12. Measurement result of sensing ridge to valley.

a low pass filter and a low gain amplifier, while the DGA is used to boost the gain of the readout circuit. By boosting the gain, it amplifies the differences between touch and un-touch actions. The overall gain of the readout circuit is shown below:

$$\frac{V_{out}}{V_{in}} = \frac{\Delta C_s}{C_f} A_{DGA} \tag{4}$$

where A_{DGA} is the gain of the DGA, ΔC_s is the difference of the adjacent sensed capacitance, and C_f is the feedback capacitance. Based on (4), if the adjacent electrodes sense ridge to ridge and/or valley to valley, the output signal will be a DC signal. If the adjacent electrodes sense a ridge and a valley, the output signal will be the same as the input signal, but with the magnitude of (4).

B. System Measurement

Fig. 11 and Fig. 12 show the measurement results of the sensing circuit with a 3.3 V input signal. Since the sensing circuit has 5 channels, only the difference of readings for a ridge and a valley is measured. When the circuit reads ridge to ridge and/or valley to valley, the output is 30 mV_{pp} as shown in Fig. 11. When the circuit reads ridge to valley, the output is 240 mV_{pp} as shown in Fig. 12. With the proposed half-diamond pattern and the sensing circuit, the difference fraction, a ridge and a valley, has an 8 times larger output than from an identical fraction. The photograph of the sensing circuit is shown in Fig. 13.

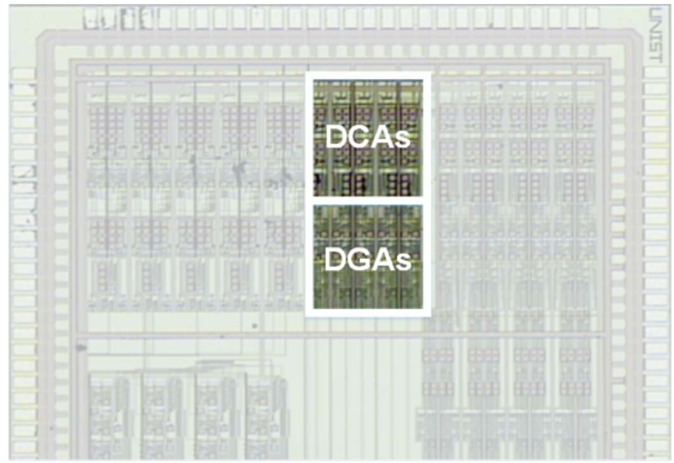

Fig. 13. Chip photograph of fabricated sensing circuit in 0.18-um CMOS process.

V. Conclusion

In this paper, an on-display half-diamond pattern fingerprint sensor and a circuit to verify the performance of the sensor are presented. To solve the large resistance and the small mutual capacitance problem, metal mesh as electrodes on a half-diamond pattern are used. The half-diamond pattern enhances the visibility of and the compatibility with an AMOLED display. The fabricated sensor has 72 × 72 channels in a 6 mm × 6 mm area. The resolution of the sensor is 322 CPI, and it surpasses the FBI criteria. The fabricated sensor achieved a 79.7% transmittance in the visible light region while that for the conventional linear pattern was 80.4%. The proposed sensor achieved static capacitances of 4.06 pF and 3.85 pF under un-touch and touch conditions, respectively. The variation of the sensed capacitance is 210 fF. The static capacitance and variation of mutual capacitance for the half-diamond pattern were 4.8 and 2.3 times larger than those for the conventional linear pattern in the same CPI. The fabricated fully differential mode readout circuit achieved 30 mVpp and 240 mVpp in identical and different fractions, respectively. The sensing circuit is fabricated with the TSMC 0.18-μm process, and it confirms the possibility of the half-diamond pattern for fingerprint detection. The proposed half-diamond pattern sensor shows considerably large variation of sensing capacitance with a high transmittance near to a conventional linear pattern sensor. With a high value of capacitance variation and an acceptable visibility, the sensor employing the half-diamond pattern is a promising candidate for identifying fingerprint on a display.

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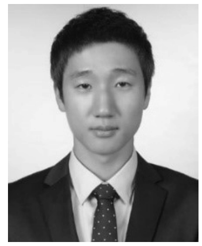

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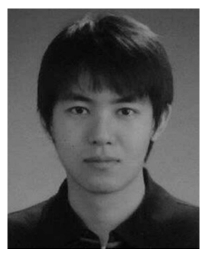

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