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A Novel FOD Solution with High-PPI Flexible Sensor under OLED Panel

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ABSTRACT

A novel FOD solution is presented in this paper. TFT-based flexible photo sensors of 725 PPI and 1016 PPI were developed and characterized. Adapted to the OLED panel with integrated pinhole imaging system, the feasibility of large area FOD function was confirmed.

1. Background

The Fingerprint-On-Display (FOD) function has rapidly become an indispensable part in recent mobile devices soon after it was first introduced into products in 2018. Nowadays, among varieties of technical routines, the optical FOD solution has become the mainstream because of the high compatibility with current mobile device structures. There are different types of optical FOD solutions in the market. One is the collimation type, in which an optical collimator made of Fiber-Optic Panel (FOP) or pinhole wafer is stacked between the OLED panel and image sensor. The collimator restricts the incident angle of reflective light from finger to ensure the optical resolution adaptable for fingerprint recognition. The other is the lenticular type, in which a small wide-angle camera is used under OLED panel with the focus set on the fingerprint plane. In these solutions, high-transparent OLED panel and small-sized CMOS image sensor are both used. These FOD solutions have achieved great success both in technology and business.

However, those FOD solutions occupy much space in mobile phone. Generally FOD sensor is attached at the back of middle bottom part of a display panel, where also the battery locates. Therefore volume of battery must be saved to add a FOD sensor. Moreover large area for fingerprint sensing is highly desired for the operation to unlock the phone, while the larger area for fingerprint sensing the smaller space left for battery [1].

In this paper, we introduced a novel FOD solution, in which a high-PPI flexible TFT-based Image Sensor (TIS) was developed to adapt the OLED panel with integrated pinhole imaging system. Under-screen fingerprint image was successfully obtained with an ultra-thin FOD module. Large area fingerprint imaging was also realized, providing customizable FOD window in size and location. The flexible FOD module structure also implies the potential applications on foldable displays.

2. Illustration of the novel FOD system

The whole FOD system includes two parts. One is a flexible 6inch FHD OLED panel, serving as the optical imaging system as well as the light source. The other part is the ultra-thin flexible high PPI TIS with AA size of 49mm*49mm, laminated onto the bottom of the OLED panel. The total thickness of the whole FOD module is only 1.297mm as shown in **Figure.1.**

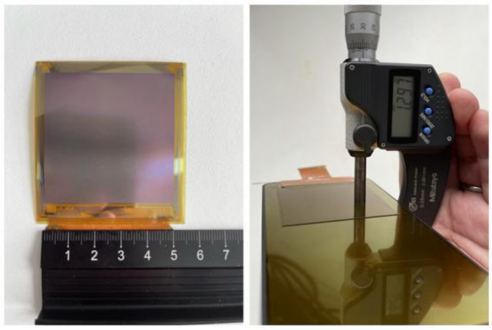

Figure.1: The left shows the flexible TIS with AA size of 49mm*49mm. On the right is the final OLED FOD module with total thickness of 1.297mm.

2.1 Integrated pinhole imaging system

A pinhole image system was integrated in the 6inch OLED panel for the benefits of low thickness, high flexibility, and low dependency of OLED panel transmittance [2, 3]. The pinhole array was fabricated in an opaque metal layer with the rest area completely shielded. Each of the pinholes forms a local pinhole imaging system, in which a shrunken, inverted image of a small area of fingerprint is projected onto the photo sensor. Finally, the fingerprint image is assembled by splicing the middle part of image fragments as shown in **Figure 2**. The optical parameters were optimized for the TIS in this system. The diameter of each pinhole is about 16um. The density of pinholes was higher than usual cases with pitch of 378um between the nearest pinholes. And the pinhole image magnification was adjusted to 0.324 by compressing the image distance so as to improve the intensity of received light on the sensor.

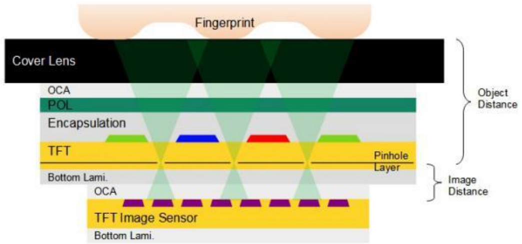

Figure.2: OLED integrated pinhole image system. The optical parameters were optimized for TIS.

2.2 High PPI flexible TIS

Since the integrated pinhole imaging system generates shrunken projection of the fingerprint image on the sensor, the sensor PPI should be much higher than usual case so as to maintain an applicable resolution. Besides, the large sensitive area was also a challenge because the very subtle fingerprint signal could be easily overwhelmed by the coupling noise during the long transmission path [4, 5]. The Active Pixel Sensor (APS) design is a very good solution to these problems.

As in **Figure 3a**, the APS pixel contains an inverted photo diode and three TFTs. The TFTs of M1, M2 and M3 form a voltage follower. The photodiode converts the photocurrent into voltage level. The power bus VDD provides voltage source for reset and signal output. The VCOM voltage is set low enough to keep the photodiode reversely biased. The pixel is first reset by M1, after which the charges stored in the capacitor Cp starts to leak through photocurrent. Consequently, the voltage level at the gate of M2 keeps dropping until reset in next frame. The voltages after reset and before next reset are both read to generate the output signal. In this way, brightness distribution is captured and processed into image from the array of the APS pixels. The TIS was fabricated on polyimide substrate with the pixel array of 1400*1400. Two types of pixel design were made with the pixel pitch of 35um and 25um respectively. The high pixel density of 725 PPI and even 1016 PPI provided enough resolution for the pinhole imaging application. The stack-up of the TIS is shown in **Figure 3b.** Each of the APS pixels contained three LTPS TFTs in the lower layers and the photodiode of doped a-Si was fabricated above. The a-Si photodiode played the key role of the photocurrent collector and the main charge container. The change of photo charges was converted into voltage in the ratio of 1/Cp. Hence, the size of the photodiode could be much smaller without too much reduction of the sensitivity, because the effective capacitor for the photodiode also becomes smaller. Vertical shifter register circuits were integrated in the sensor panel as well to generate row scan timing for reset and signal reading. A multiplexer circuit of 1:4 ratios was also fabricated to transmit the column output signals to four lines of the output buses. A separated shifter register circuit was made to execute the column scanning of the multiplexer.

2.3 Signal read-out system & module assembly

A signal read-out system based on FPGA was developed for timing generation and signal processing. The read-out signal was amplified by 10 times. In the case of that the sampling area was smaller than the sensor AA, a local sampling timing was executed. During the scanning, the scanning period in the target sampling area was set longer for better signal reading. While in the non-sampling area, the scanning was rapidly skipped without any sampling. In this way, the time for each sampling frame was compressed.

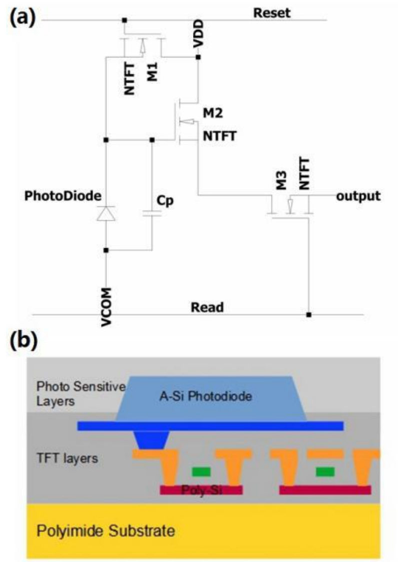

Figure.3: (a) The pixel circuit of a typical APS design. (b) The non-coplanar stackup of the TIS.

3. Test results

The photo response of the TIS was first characterized. And then the feasibility of FOD function was tested.

3.1 Sensitivity of the TIS

In the TIS pixel of 35um pitch, the photosensitive area was about 545 um^2. The photo response was tested under the different exposure time as shown in **Figure 4**. Luminance of a plane light source was calibrated as a measure of the sensitivity. For the 133ms exposure time, the output signal rose with the luminance and reached the saturation point at 7 nit. The sensor showed good linearity in photo response before saturation. The dynamic range was about 55.6dB. When the exposure time was prolonged to 880 ms, although the saturation point came earlier at 1.3 nit, the dynamic range increased to 59.67dB because the sensor was more sensitive to weaker luminance. The ratio of signal slope of photo response was used to represent the sensitivity. The sensitivity of the pixel of 35um pitch was about 1.99 V/nit·s. However, for the smaller pixel design of 25um pitch, in which the photosensitive area decreased to 179 um^2, the sensitivity dropped to 1.16 V/nit·s. One of the reasons about the sensitivity decrease in high PPI pixel was that, part of the photodiode was less sensitive than the other parts, especially those near the edge of the a-Si photodiode. Smaller size of photodiode means larger proportion of less sensitive part, leading to the decline of the total sensitivity. The stray capacitor also played an important role. As the size of photodiode becomes smaller, the diode capacitance dropped as well. The total Cp comprised of both the diode capacitance and the stray capacitance. When the proportion of the diode capacitance decreases in the total Cp, the sensitivity will drop dramatically.

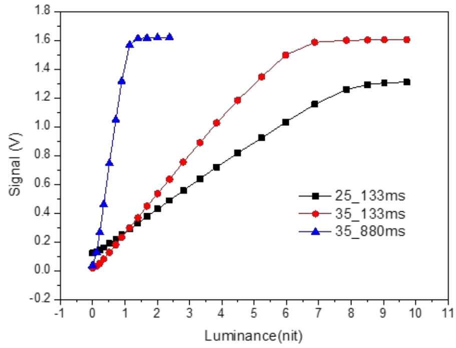

Figure.4: Photo response curves of the TIS pixel with photodiode. The red & blue lines show the photo response of pixel pitch of 35um with the exposure time of 133ms & 880ms respectively. The black line shows the photo response of pixel of 25um pitch in 133ms exposure time.

3.2 Full-sensor image acquisition

A striped patterned mirror is attached on the image sensor under the ambient light, and the full image (49mm x 49mm) was obtained by the image sensor with the exposure time of 880ms. As shown in **Figure 5**, the stripes with 100um, 150um, 200um, 250um and 300um interval were distinguishable.

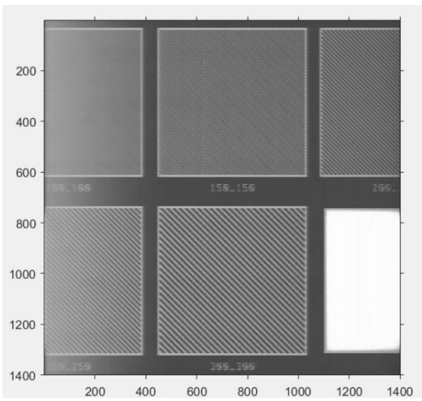

Figure.5: The full image (49mm x 49mm) of tested pattern was taken by the image sensor with the exposure time of 880ms.

The light response curves were collected every 200 rows, as shown in **Figure 6**. The fluctuation range of the slopes of the lines before saturation is -7.1% to 8.5%. As shown in **Figure 7**, the sensitivities of the pixels in the middle part of the active area are a little higher than the edges, due to the slight uneven etching. And because of the loading on data lines, the slopes of the big Num. Rows are larger than the small Num. Rows. However, the fluctuation of the pixels' sensitivity is still acceptable.

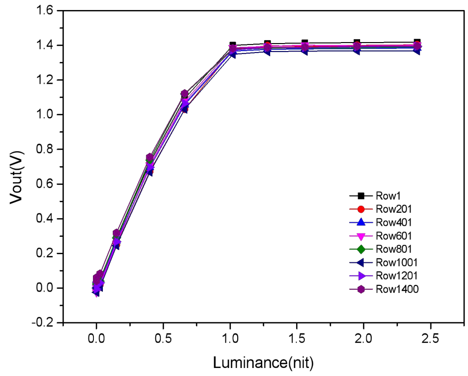

Figure.6: The light response curves were collected every 200 rows.

3.3 FOD tests

The FOD function was also tested with OLED module. Fingerprint images were captured from different locations of the sensitive area. Each of the FOD windows covered 200*200 pixels (7mm*7mm) in the 35um pixel pitch TIS, with the light source provided by the illumination of OLED panel.

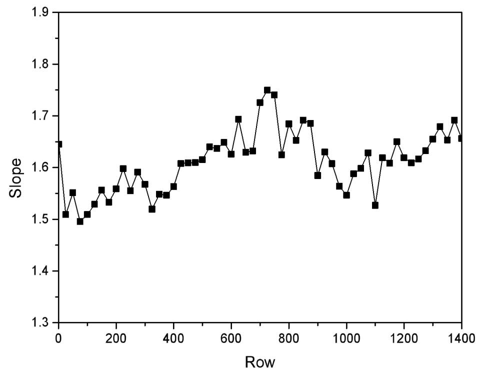

Figure.7: The slope of the light response curves (sensitivity) before saturation. The sensitivity fluctuation was no more than ±10%

As shown in **Figure 8**, in different parts of the sensitivity area, the fingerprint images captured by TIS were clearly recognized. With the exposure time of about 690ms, the fingerprints signal-to-noise ratio (SNR) was about 8.33. Extended FOD window was also tested successfully in 400*400 pixel array of TIS, covering 14mm*14mm area. The fingerprint images from TIS of 25um pixel pitch was also captured under that same condition, as shown in **Figure 9.** Since the TIS of 25um pixel pitch had lower sensitivity than that of the 35um pitch pixel, a faded fingerprint image was obtained as expected, but still distinguishable. The fingerprint SNR was about 6.67.

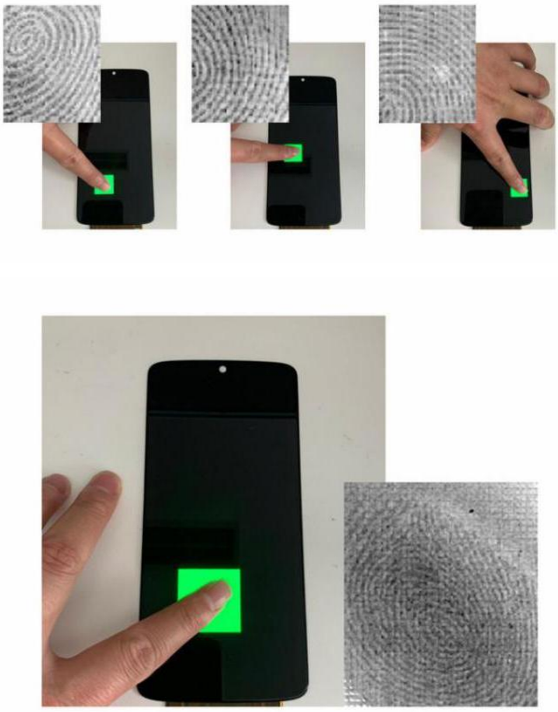

Figure.8: Fingerprint images were captured in TIS of 35um pixel pitch, the FOD window could be set to different locations and fingerprint images were clearly recognized. Larger area fingerprint images of 14mm*14mm were also obtained.

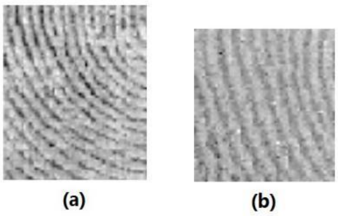

Figure.9: (a) The fingerprint image taken from TIS of 35um pixel; (b) The fingerprint image taken from the sensor of 25um pixel, the 200*200 pixel array covered 5mm*5mm area.

4. Conclusion & Discussion

In conclusion, high PPI flexible TFT-based image sensors were developed. Feasibility of large FOD function was confirmed with the APS pixel design under the OLED panel with integrated pinhole imaging system. Sensitivities in different designs of pixel pitch were tested. Full-sensor imaging ability was confirmed in 49mm x 49mm area with sensitivity fluctuation less than 10%. Although the sensor with 25um pixel pitch was found less sensitive than the design of 35um pitch pixel, the fingerprint images were both captured under OLED panel successfully.

Recently, the technology progresses in foldable display are very remarkable. But currently there is hardly any of the applicable FOD solution for foldable products. One of the difficulties is the rigidity of the parts of FOD sensors. In our study, the ultra-thin, fully flexible module features has implied the potential of application in foldable OLED products.

5. References

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