Novel Optical Fingerprint CMOS Image Sensor for Ultra-thin Module

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***Abstract*—** In this paper, a novel image sensor with special pixel structure dedicated for direct imaging was proposed. In-chip Infrared (IR) filter was integrated to back-illuminated CMOS image sensor to block long-wavelength light from outside. It was verified that the high-resolution image of fingerprints can be formed without optical lens by narrowing the angle of view (AOV) of the pixel. The new pixel structure having narrow AOV was designed by optimizing micro lens diameter, optical height, and aperture size. The in-chip IR filter helps to reduce module thickness, which is a key feature of the module for on-display fingerprint sensor. The experimental results reveal that the newly designed CMOS sensor can be utilized as an ultra-thin fingerprint sensor.

I. Introduction

Recently, the application fields of the CMOS image sensor have been expanded to various fields over the years, such as automotive sensor, Time-of-Flight (ToF) sensor, and optical fingerprint sensor for mobile applications. Since 2019, mobile phones using under-display fingerprint sensors have been released, and have become the mainstream of biometric recognition for mobile handsets [1][2]. Image sensors for fingerprint recognition have different characteristics from those for general photography, so a special pixel structure is needed. Required features for fingerprint sensor are customized optical structure to capture fingerprints at a short object distance, sufficient sensor sensitivity for imaging under display screen and prevention of interference with long-wavelength light from outside. Additionally, since the sensor should be located just under the screen, size is limited and sensor parts should be invisible. In this study, we propose a direct imaging type fingerprint sensor which enables ultra-thin camera module based on Samsung's unique pixel technology. Clear fingerprint images are obtained using novel pixel structure under low illumination to suppress OLED screen degradation and a short object distance. With special color filter stack, we could make the sensor invisible when located beneath the display panel. Also, the in-chip IR cut filter using multiple thin films was able to prevent interference by infra-red rays outdoors.

II. Design concept and basic principle

Basic principle of under display optical fingerprint sensor is described in Fig. 1 (a). The fingerprint images are created using the contrast induced by the difference of refractive indices between ridge and valley of the finger. The ridge of the finger adheres to the display surface whereas the valley is filled with air. As the light emitted from display panel to finger, relatively little light is reflected due to the similar refractive index between display panel (n ~1.5) and the ridge (n ~1.4), resulting in a dark image. On the other hand, relatively larger amount of light is reflected due to the refractive index difference between display panel (n ~1.5) and the valley filled with air (n ~1.0), resulting in a bright image. As a consequence, contrast between ridge and valley forms bright/dark images of a finger. Fig. 1 (b) is a sample image taken by the optical fingerprint sensor. Optical fingerprint sensor can be divided into three types, as represented in Table 1. The first type is a pinhole camera type which is composed of conventional image sensor and extra pinhole array. Pinhole type sensor shows poor sensitivity, resolution and Moiré phenomenon. The second type is macro camera module type which is most commonly used currently. However due to the thickness of the module containing optical lens, the sensor cannot be freely placed. The third type is direct imaging type which uses a special sensor design. One of the biggest features of this type is that it is a single chip structure without additional components for imaging. Therefore, we can make a thin module with simple process. The thin fingerprint sensor module can allows for free placement in screen.

A. *Direct imaging optical structure design*

In order to implement a direct imaging optical fingerprint sensor, narrowing angle of view (AOV) of each pixel is essential because the AOV directly determines the resolution and sensitivity of the sensor. Fig. 2 depicts the schematic images that show the sensor resolution according to the pixel's AOV. In the case of pixels having a wide AOV, the view of the pixel overlaps and shows a blurred image whereas the view of pixel with narrow AOV does not overlap each other and shows a relatively clear image. As described in the schematic image, one of the most important factors for sensor resolution is the angular response of pixel, which closely related to the AOV. In order to minimize the AOV, direct light signals should be maximized, and plain light signals should be minimized. Fig. 3 shows the angular response according to the incident light angle of the conventional image sensor pixel and fingerprint sensor pixel. In the case of conventional pixels, incident light angles of 10 degrees or more show higher than 80% of signal compared to that of direct incident light. While, a newly designed pixel for direct imaging fingerprint sensor blocks most of the plain light having incident angle above 5 degrees, resulting in a narrow AOV. As can be seen, for narrowing the AOV, a novel pixel structure is necessary. Fig.

4 shows the vertical structure of conventional and novel pixel for fingerprint sensor. The main factors that determine a pixel's AOV are (a) micro lens diameter, (b) optical height and (c) aperture size. Compared to conventional image sensor pixel, pixel for fingerprint sensor has higher lens curvature, optical height and reduced aperture size in order to effectively block the plain light. As mentioned above, the AOV of the pixel could be controlled by micro lens diameter to optical height ratio (a:b ratio) and micro lens diameter to aperture size ratio (a:c ratio), so these factors were verified to find the optimum structure, as shown in Fig. 5. Additionally, to secure optimum pixel performance, not only AOV but also sensitivity is important since the sensitivity also affects the SNR of pixel. So it is important to find an optimum structure with appropriate AOV and sensitivity. As a result, by changing the a:b and a:c ratio values, the pixel structure showing optimum AOV, sensitivity, and SNR performance was achieved.

In fact, in case of an optical fingerprint sensor, high image resolution as the general photography is not required, and since the distance between the ridge is about 200-800μm, it is only necessary to meet a resolution that can distinguish this level. Therefore, since micrometer sized pixels are not required, dozens of micrometer sized pixels are merged and used as one unit pixel of the sensor. The merged pixels are denoted as a unit block in this paper. In this case, it is advantageous to let these pixels look at the same point to enhance the sensor resolution by minimizing the AOV of the unit block, which we named the "block shrink technology". Fig. 6 shows the schematic images of unit blocks with and without the block shrink technology. Block shrink is a technology that shrinks the micro lens and aperture of the pixel based on the center of the unit block so that all pixels could look at the center of the unit block, as shown in the schematic images. As a result the SNR of sensor with block shrink increased by about 1.0dB due to the increased resolution, as shown in Fig.7.

B. Invisible sensor beneath the screen

Besides the resolution and sensitivity of the pixel, several technologies are required for the optical fingerprint sensor to be applied to mobile applications. One of the important properties of the fingerprint sensor is to prevent from being visible beneath the display panel. In order to satisfy this, we have implemented the pixel ebonizing technology by stacking different color filters on the top of aperture metal layer. By stacking red, green and blue color filters, the stacked color filter layers absorb the visible light and also suppress the reflected light caused by the metal layer, resulting in the ebonized pixel. Fig. 8 (a) and (b) confirms that the pixel was successfully blackened by the stacked color filters on the metal layer of the pixel.

C. Prevention of Infrared interference

Infra-red (IR) blocking capability is important for the fingerprint sensor because IR light can penetrates the fingers, display and reach the sensor. When the IR sunlight penetrates and reaches the sensor, the contrast between the ridge and valley would disappear and most of the pixels would be saturated since the illuminance of sunlight is much larger than the light emitted from the panel, as described in Fig. 9. In order to inhibit the IR interference, an external IR cut filter is usually mounted on the top of the sensor. However, for the optical fingerprint sensor, the IR cut filter is required to be integrated into the sensor to reduce the distance between finger and sensor in order to enhance the resolution. Consequently, pixel consists of in-chip IR cut filter was designed. Table 2 shows a schematic structure of sensor with external IR filter, no IR filter and in-chip IR cut filter, respectively. In-chip IR cut filter which is composed of multiple pairs of layers having relatively high and low refractive index was deposited. In this study, 11 pairs of titanium dioxide and silicon dioxide layers were used, which is a common material for light reflecting filter [3]. The normalized quantum efficiency (QE) spectra show that the light with wavelength over 650nm was successfully suppressed by the in-chip IR cut filter. To confirm the actual effect of the IR cut filter, fingerprint images were taken by the each sensor. Compared to the images taken by the sensor without any IR cut filter, those taken by the sensor consists of pixel with in-chip IR cut filter show much distinct details of fingerprint, which indicates that the in-chip IR cut filter successfully blocked the external light.

III. CONCLUSION

A novel pixel structure having narrow AOV was developed for lens-free fingerprint sensor based on back-illuminated CMOS image sensor. By re-designing the optical structure of the pixel, sharp and clear fingerprint images were successfully achieved using lens-free fingerprint sensor. Several pixel technologies were also developed for mobile application. Color filter stacking technology was applied for ebonizing the sensor in order to prevent from being visible under display panel, and IR cut filter was integrated into the pixel to reduce the thickness of sensor module. These experimental results reveal that the modified CMOS image sensor can be utilized at fingerprint sensor applications.

ACKNOWLEDGMENT

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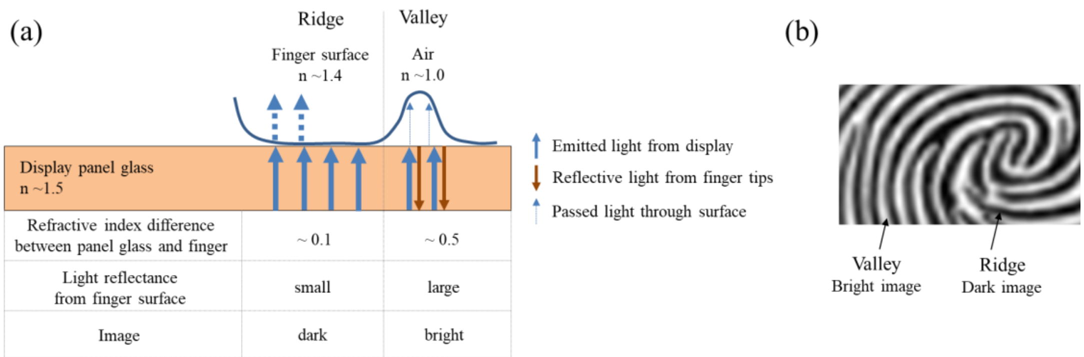


Fig.1. (a) Conceptual diagram of optical fingerprint imaging. Ridge with low reflectance makes a dark image and a high reflective valley produces a bright image. (b) A sample image using optical fingerprint sensor.

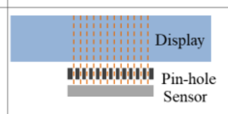
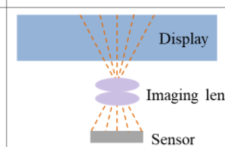
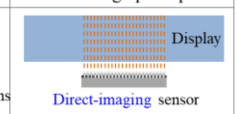
Technology		Pin-hole type	Camera module type	**Direct-imaging type**
Structure	Imaging component	Pin-hole	Camera lens	(integrated into sensor)
	Pixel	Conventional	Conventional	Custom fingerprint pixel
	Module			
Features	Sensitivity	Poor	Good	Very good
	Resolution	Poor	Very good	Very good
	Module thickness	Good	Poor	Very good
	Assembly convenience	Good	Poor	Very good

Table1. Structural and charatersistic comparision of three types of optical finger print sensors.

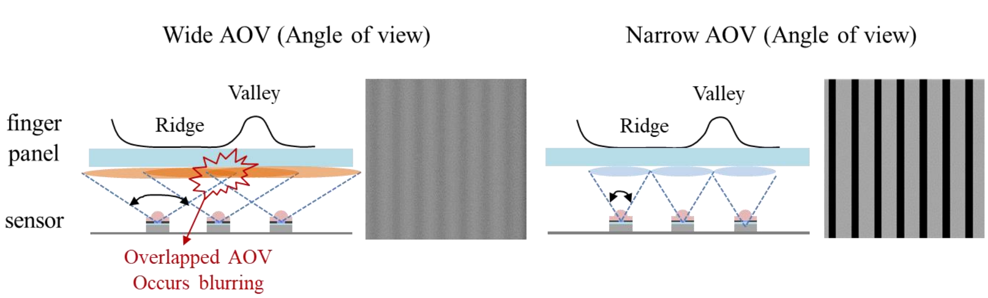


Fig. 2. Schematic image of sensor resolution in terms of angle of view(AOV) of a pixel.

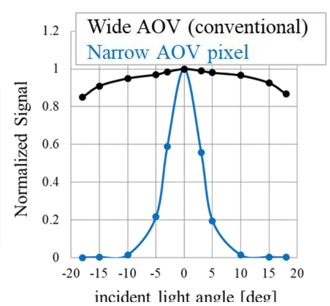


Fig. 3. Angular response of conventional image sensor pixel and direct imaging fingerprint sensor pixel.

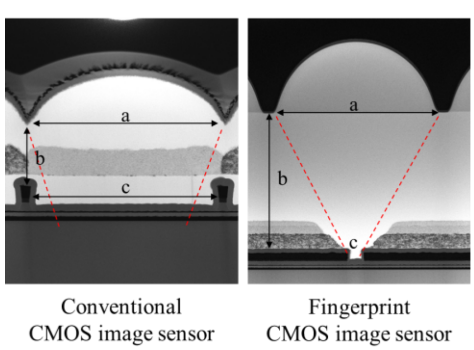


Fig. 4. Vertical TEM images of conventional and modified pixel structure for direct imaging fingerprint sensor.

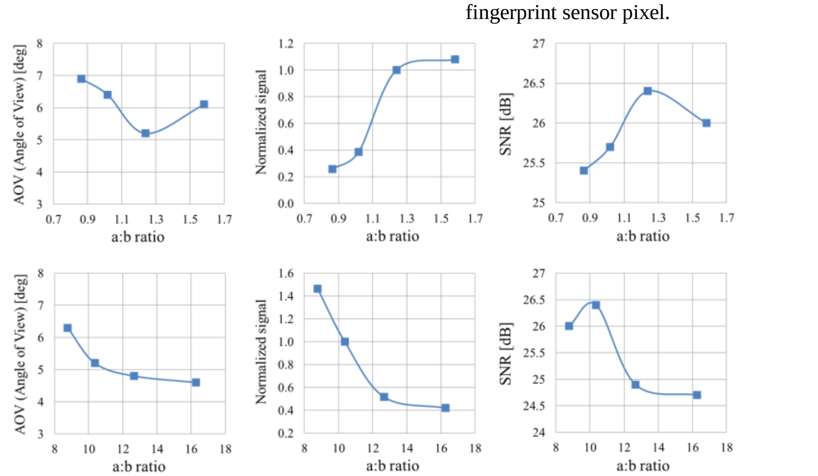


Fig. 5. Angle of view (AOV), normalized signal, and SNR of the pixel in terms of micro lens diameter-optical height ratio (a:b ratio) and micro lens-aperture size ratio (a:c ratio).

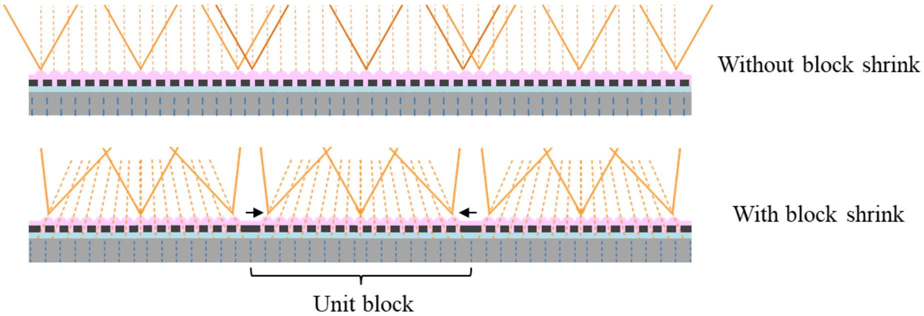


Fig. 6. Schematic images of fingerprint sensors with and without block shrink technology.

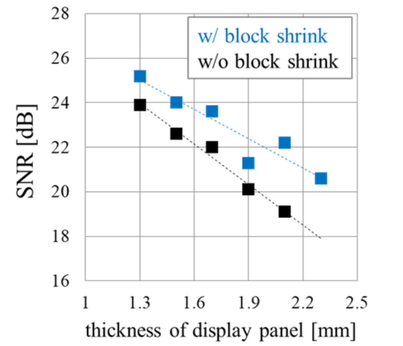


Fig. 7. SNR of sensors with and without block shrink in terms of display panel thickness.

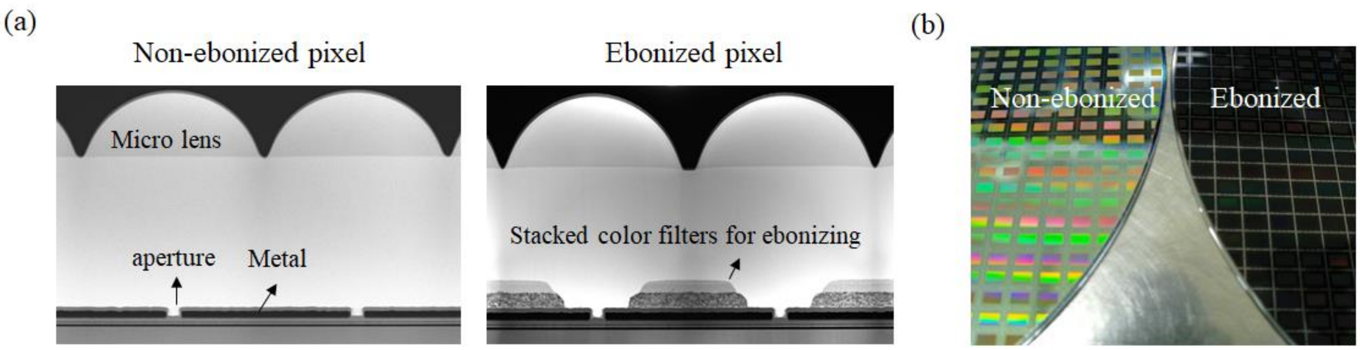


Fig. 8. (a) TEM images of non-ebonized and ebonized pixel. (b) Wafer-level feature of non-ebonized and ebonized pixel.

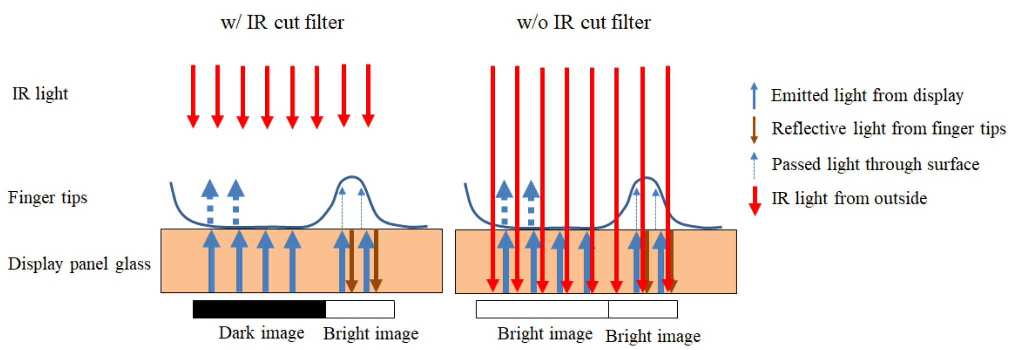


Fig. 9. Schematic images of IR interference effect caused by sunlight to the fingerprint sensor with and without IR cut filter.

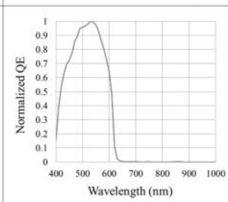
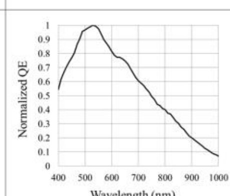
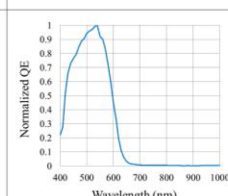
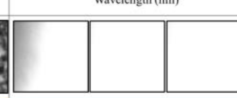
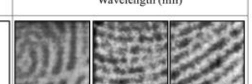
Technology	External IR cut filter	No IR cut filter	**On-chip IR cut filter**
Structure	Display IR cut filter Sensor w/o IR cut filter	Display Sensor w/o IR cut filter	Display **Sensor w/ IR cut filter**
Spectrum			
Finger tips image			
Module thickness	Thick	Thin	Thin
IR interference	Very good	Poor	Very good
Assembly convenience	Poor	Very good	Very good

Table1. Structure, QE spectra, photographic image and characteristic compare of fingerprint sensors with external IR cut filter, no IR cut filter and in-chip IR cut filter, respectively.