Optical Fingerprint Sensor Based on a-Si:H TFT Technology

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Abstract
In this report, hydrogenated amorphous Si (a-Si:H) TFT technology based optical fingerprint sensors are demonstrated. Our a-Si:H fingerprint sensor technology has the advantages over CMOS fingerprint sensor technology with regard to internal quantum efficiency in accordance with our simulations, expandability to large area, insensitivity to IR light and cost efficiency. We have successfully developed three types of fingerprint sensor modules which we name thin optical touch (TOT), hidden optical touch (HOT) and hidden under display (HUD) sensors. Each sensor module is designed accordingly for a particular application. Our sensor size ranges from small size (4.0 mm x 8.0 mm) for smartphone user identification to 4 finger size (3.2” x 3.0”) for public security check.

Author Keywords
Optical fingerprint sensor; a-Si:H TFT technology; Internal QE; Under display; Under glass; FAR; FRR.

1. Introduction
Biometric fingerprint technology has been striding forward with constantly growing demand for more secure and more reliable personal authentication means in the wake of highly security required networked society. Fingerprint sensor technology utilizes various physical mechanisms to capture the electronic images of fingerprints via handheld devices, personal computers, and smartphones, which have been rapidly embraced across almost all demographics around the world. Optical, capacitive, acoustic, & thermal fingerprint sensor system have been demonstrated through a variety of commercial products and are being explored in a competitive manner by numerous industry and research groups [1].

In this report, we present a hydrogenated amorphous Si (a-Si:H) thin-film based optical fingerprint sensor technology and its products although quite a number of optical fingerprint sensor devices rely on CMOS technology in the current market simply because CMOS image sensor technology developed for digital cameras could be transformed for an optical fingerprint sensor device without technical difficulty since a-Si:H thin film based fingerprint sensors can be fabricated from a small size for smartphone application to large 4 finger sensor or palm film based fingerprint sensors can be fabricated from a small size (4.0 mm x 8.0 mm) for smartphone user identification to 4 finger size (3.2” x 3.0”) for public security check.

It is known that the readout circuits for TFT based electronics are separately fabricated using CMOS technology. An add-on readout IC is bonded onto the data lines of the TFT sensor by chip on glass (COG) process or flex on glass (FOG) process to make sensor module as compact as possible. In the readout IC, there are charge amplifier, noise reduction block and 16 bit ADC to read out the signals from pixel array.

2. Simulated Internal Quantum Efficiency (QE)
Optical finger sensor commonly employs p/n diode structure to detect the reflected light from the surface of finger. In this section, we will compare a-Si:H thin film p-i-n diode against crystalline silicon p+i/n diode from the perspective of opto-electrical characteristics of diodes which could be a strong indicative of how efficiently a signal detector can convert the incident light to electric current. When the diode is exposed to the incident light, it generates photo-current and the ensuing output current will be read out in voltage or current depending on the pixel architecture and the subsequent readout circuit. It is noted that the efficiency of photo-current generation by the diode, internal quantum efficiency (QE) is defined as

\[
QE(\lambda) = \frac{J_{ph}(\lambda)}{q\Phi_{in}(\lambda)}
\]

where \( J_{ph}(\lambda) \), \( \Phi_{in}(\lambda) \), & \( q \) are photo-current, incident photon flux and elementary charge, respectively.

As expressed in Equation (1), QE is a function of wavelength and has the primary variable of \( J_{ph}(\lambda) \). The photo-current term is expressed as

\[
J_{ph}(\lambda) = \int_{0}^{\lambda} G(x, \lambda) dx - \int_{0}^{\lambda} R(x, \lambda) dx - J_{no}(\lambda) - J_{p}(\lambda)
\]

where \( G(\lambda) \), \( R(\lambda) \), \( J_{no}(\lambda) \), and \( J_{p}(\lambda) \) are optical generation and recombination current, electron back diffusion current at the front contact (p layer) and hole back diffusion current at the back contact (n layer), respectively. \( L \) is the total thickness of device. Both \( J_{no}(\lambda) \) and \( J_{p}(\lambda) \) terms are negligible amounts unless the contacts are inadequately designed [3]. As Equation (2) above indicates, higher optical generation and lower recombination current are required to achieve a high photo-current leading to a high QE as expressed in Equation (1).

Optical generation is controlled by absorption properties of material. The optical absorption properties of a-Si:H and silicon material are plotted in Figure 1. As shown in Figure 1(a), a-Si:H material has higher optical absorption in the range of 0.4 to 0.75 \mu m than Si layer whereas Si has stronger absorption in longer wavelength region (> 0.75 \mu m) than a-Si:H film. In other words, under visible light, a-Si:H based diode will inherently generate more photocurrent than Si based diode.

In this report, we employ analysis of microelectronic and photonic structures (AMPS) 1D simulator to assess opto-electronic characteristics of a-Si:H p-i-n diode and silicon p+i/n diode [4].
To compute the recombination current expressed in the Equation (2) above, we account for both band-to-band and Shockley-Read-Hall recombination mechanisms in this simulation. A-Si:H material is known to have wider band gap ($E_g$) than its optical band gap ($E_{opt}$) [5]. We input respective 1.80 eV and 1.12 eV as the band gap of a-Si:H and Si layers with other device parameters such as optical absorption, defect densities, doping concentration and etc. for each device [3], [4], [6]. For this comparative analysis between these two diode structures, we apply the same reverse bias condition and the same total thickness of diodes for the simulations. For Si diode, we add a thicker diode case (i.e., 2x thickness) to see the effect on internal QE in longer wavelength region.

Figure 1(b) shows simulated internal quantum efficiencies (QE) of a-Si:H p-i-n and Si p+/n diode. Figure 1(b) shows simulated internal quantum efficiencies (QE) of a-Si:H p-i-n and Si diodes. As shown in the simulated internal QEs, a-Si:H p-i-n diode has higher QE output in the most of visible wavelength region than Si p+/n diode, which could be indicated by the optical absorption properties shown in Figure 1 (a). It is noted that Si diode demonstrates higher QE in blue (< 0.48 µm) compared to a-Si:H diode which is not consistent with optical generation component. It is known that for Si p+/n diode structure, heavily doped p+ layer is formed at the surface to passivate the defects so that the highest electric field is located at p+/n junction area close to the surface and the strength of electric field is quickly decreased as it gets deeper away from the surface of Si. [7], [8] The simulated internal QE response of Si diode also reflects the electric field inside the diode; that is, the QE response is high in blue due to very strong electric field and becomes lower as the wavelength gets longer (i.e., deeper absorption). In the case of external QE, the blue response from Si diode will be much lower than that of internal QE since blue incident light is attenuated due to absorption through various layers and reflection at the interfaces even before the blue light impinges upon the surface of diode.

When the thickness of n type region of Si p+/n diode is increased by two times, as shown in Figure 1 (b), overall QE response including near IR wavelength region is enhanced because the thicker diode structure leads to higher optical generation current. Although the increased Si diode thickness is much thicker than the ones being used for CMOS image sensor, we simulated to examine the effect of thickness of Si diode on internal QE output. Even after the thickness of Si p+/n diode is increased by two times, the resulting QE response of Si diode is still lower in the range of 0.5 µm to 0.7 µm wavelengths than a-Si:H p-i-n diode’s response.

3. Application Results

3.1 Thin Optical Touch (TOT) Sensor

We first introduce so-called Thin Optical Touch (TOT) sensor illustrated in Figure 2 where we position a TFT sensor between a protection layer and a back light source. A fiber optical plate (FOP) is put on the top of optical fingerprint sensor not only to protect the TFT sensor from ESD damage or scratch but also to focus the incident light on TFT sensor. An optical adhesive layer between FOP and TFT improves optical coupling. The top surface of the FOP serves as the touch surface of finger as well.

A back light source (usually an LED and a light guide board included) illuminating the light for the fingerprint imaging is placed on the back of the TFT sensor. Since both a-Si:H and finger have a good absorption rate at blue wavelengths, a 460nm LED is placed as a light source at the side of the light guide board to obtain high-quality SNR performance.

Figure 2. Structure and optical paths of TOT based fingerprint sensor.

We have developed several products based on the TOT technology, and applied for security check and user identification fields. The active area size ranges from FAP10 (0.5"x0.65") up to FAP60 (3.2"x3.0") [9]. As explained earlier, our sensor technology is adaptable to a variety of sizes and form factors. The compactness of our sensor module and outstanding image quality are noticeable compared to the other sensors in the market.

As an example of TOT sensor module, 1-finger sensor module is displayed in Figure 3 (a) and a raw image captured by the sensor is shown in Figure 3 (b). This one-finger sensor module met both FBI and China GA SPECs and has gotten PIV10 and China GA/T 1011-2012 certifications [10]. For some high security level applications, 2-finger images are required. Figure 4 (a) is a picture of 2-finger sensor module (i.e., FAP45, 1.6"x 1.5” active area)
meeting Appendix F defined by FBI [9].

![Figure 3](image)

**Figure 3.** Picture of 1-finger sensor module (i.e., FAP10) (a) and fingerprint raw image captured by the one finger module.

An image of 2 fingers captured by our FAP45 sensor module is shown in Figure 4 (b). In addition, we successfully developed 4-finger sensor (i.e., FAP60) module which is not shown here.

![Figure 4](image)

**Figure 4.** Picture of 2-finger sensor module (i.e., FAP45) (a) and fingerprint raw image captured by the two finger module.

### 3.2 Hidden Optical Touch (HOT)

As a user identification device with high reliability and durability, fingerprint sensor under cover glass has been demanded by hardware component industry. We have developed a fingerprint sensor module under cover glass and named Hidden Optical Touch (HOT) which employs a-Si:H thin film based sensor without FOP incorporated. As illustrated in Figure 5, a glass platen is placed on the top of optical fingerprint sensor without FOP. This glass platen is also served as the cover glass of tablet display or smartphone. A-Si:H TFT sensor is attached to the cover glass with optically clear resin (OCR) or optically clear adhesive (OCA). By using OCR/OCA, not only TFT sensor is attached to the cover glass but also the light reflection caused by the difference in refractive indices is reduced. To achieve high-quality image even with thick cover glass, a glass platen with thickness of 0.5 mm x 10.0 mm and the thickness of cover glass used is 0.7 mm. We note here that our HOT fingerprint sensor module can be operated at FAR of 1/50,000 and the corresponding FRR less than 1% (i.e., about 0.73 %) as shown in Figure 6. For some high security applications, very low FAR (< 1/10,000) is required so that the matching FRR could be a little higher than 1%.

![Figure 5](image)

**Figure 5.** Structure and optical paths of HOT sensor.

We optimize the sensor area to balance between achieving better performance of FRR/FAR and maintaining the compactness of sensor module. Because we are able to accomplish high-quality fingerprint image even with 1.5mm cover glass, our HOT sensor modules are being evaluated by smartphone and tablet device manufacturers.

![Figure 6](image)

**Figure 6.** Receiver operation curve (ROC) plotting FAR vs. FRR data collected by HOT sensor module.

Figure 6 depicts a receiver operation curve (ROC) plotting FAR versus FRR based upon the data collected from six fingers of 30 users with our HOT sensor module. The active area size is 9.0 mm x 10.0 mm and the thickness of cover glass used is 0.7 mm. We note here that our HOT fingerprint sensor module can be operated at FAR of 1/50,000 and the corresponding FRR less than 1% (i.e., about 0.73 %) as shown in Figure 6. For some high security applications, very low FAR (< 1/10,000) is required so that the matching FRR could be a little higher than 1%.

### 3.3 Hidden Under Display (HUD)

As the most of major smartphone manufacturers are keen to realize biometric fingerprint sensor under OLED display, we have made intensive effort to develop Hidden Under Display (HUD) sensor module. Although HUD’s TFT sensor architecture is conceptually the same as the TOT and HOT sensors mentioned earlier, TFT pixel design such as the fill factor of photodiode is further optimized for this application. As illustrated in Figure 7, emitting light from OLED display serves as a light source for fingerprint imaging. The reflected OLED light from the surface of finger could cause crosstalk between the pixels of fingerprint sensor. In order to obtain high-quality fingerprint images, a collimator is used to focus the reflected light onto the surface of TFT pixel array. The collimator cuts off the light at high incidence angle so that it reduces crosstalk between the pixels.

When the fingerprint sensor is incorporated under the OLED display, our fingerprint sensor provides large enough sensing area and the quality of the information.

![Figure 7](image)

**Figure 7.** Hologram and optoelectronic device (HOT) for fingerprint detection.
(e.g., 12mm x 20mm, 12mm x 40mm, 40mm x 51mm and etc.) so that phone users have much more area to enroll the fingerprint and wake up the phone. Larger biometric sensing area is not only a preferred feature demanded by phone manufacturer but also an efficient way to improve both FRR & FAR performance. Especially when a user has a poor finger condition such as less contact area or dry finger surface, larger active area renders more useful information extracted from the fingerprint images.

Figure 7. Structure and optical paths of HUD sensor.

Figure 8(a) illustrates a HUD module (active area of 40mm x 51mm) under OLED display of smartphone (e.g., Vivo Apex). The area enclosed by red dashed lines at the bottom of the display corresponds to the fingerprint sensing area.

We have integrated our HUD modules into smartphone with flexible OLED displays in the market (e.g., Vivo Apex & Xplay6 smartphones and Samsung flexible OLED display with QHD revolution). The corresponding raw image of thumb is depicted in Figure 8 (b). The size of image is larger than those from other fingerprint sensors available in the current market. In addition, we have also built another type of HUD sensor for the smartphones with rigid OLED display (e.g., Vivo X20 smartphone and Samsung rigid OLED display with FHD revolution). The layer stack of rigid OLED display is different from that of flexible OLED display. A key difference is the presence of an air gap between the two glass substrates of the rigid OLED display (as shown in Figure 7). Because of the air gap, the quality of fingerprint image captured by the sensor under rigid OLED display could be degraded because of light reflection & scattering. To resolve the degradation of image quality, we have optimized our sensor structure such as the design of collimator and image signal processing for the rigid OLED display. As a result, a high quality fingerprint image (not displayed here) could be obtained even under rigid OLED display.

It is noted we are able to fit our large area HUD sensor module into a smaller given space inside the smartphones with flexible OLED display as smartphones get thinner than the previous ones. Because our thin film based fingerprint sensor technology is compatible with both flexible and rigid OLED displays of smartphones, integration of our optical sensor with OLED display panel is being developed with display industry.

4. Summary

Our fingerprint sensor based upon a-Si:H TFT technology has advantages over silicon based fingerprint sensors in terms of internal QE within most of visible light range based on our simulations, expandability to large area, insensitivity to IR light, compactness of sensor module, and cost efficiency. We have successfully developed and demonstrated three major types of sensor modules optimized for respective applications; that is, Thin Optical Touch, Hidden Optical Touch, and Hidden Under Display. We named are either in mass production mode or being qualified for mass production. These products are applied for biometric fingerprint identification methods such as smartphone user authentication, PC user authentication incorporated with touch pad, security checking device, electronic locker, and attendance machine.

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6. References