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A Hydrogenated Amorphous Silicon Thin-Film Transistor Optical Pixel Sensor for Ameliorating Influences of Ambient Light and Reflected Light

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ABSTRACT This paper proposes a hydrogenated amorphous silicon thin-film transistor-based (a-Si:H TFT) optical pixel sensor. The proposed optical sensor compensates for variations of ambient light using photo TFTs that incorporate with three primary color filters, and a designed active load is utilized to release the photocurrent from the noise of reflected light. Measurement results reveal that the proposed sensor suppresses the effect of ambient light within the intensity of 12 560 lux and does not react to a blue light with an intensity of 588 lux, proving that the proposed optical sensor remains highly reliable under heavy ambient light and avoids the interference of reflected light.

INDEX TERMS Hydrogenated amorphous silicon thin film transistors (a-Si:H TFTs), optical sensor, pixel sensor.

I. INTRODUCTION

Among various thin-film transistors (TFTs) processes, hydrogenated amorphous silicon (a-Si:H) has attracted much attention because of low-cost fabrication, high yield, high uniformity for large-size displays, and high photosensitivity [1]–[3]. In particular, the high photo-sensitivity of a-Si:H TFTs favors various applications of TFT-based optical sensors, including optical proximity sensing [4], X-ray image scanning [5], and optical input sensing [6]–[9]. Furthermore, integrating TFT-based optical sensors into an interactive panel or large display can realize multi-input functionality without complex algorithms, unlike conventional large capacitive touch panels, supporting writing with a light emitting diode (LED) pen [10]. Numerous investigations of optical pixel sensors have been published [6]–[9]. In 2004, Abileah *et al.* [7] proposed an optical sensor to sense shadows of fingers or illumination from a laser pointer. By inducing photocurrent of the photo TFT under sufficient illumination, the optical sensor discharges the charges stored in a storage capacitor and then transmits these sensed charges through the readout TFT. However, the ambient light strongly affected the sensing results of the aforementioned study, leading to false detection. Our previous work [8] proposed an optical sensor integrating photo TFTs covered by RGB color filters to sense optical signals from one of the three primary colors for compensation for the ambient light effect. However, if the hands of a user touch the surface of the panel during the LED pen-writing process, then illumination from the display image may be reflected to other sensors. This reflected light may cause false detection by other sensors, leading to a malfunction of the display. To increase the signal-to-noise ratio (SNR) of optical sensors and prevent false detection on account of reflected light, the optical sensor must not respond to reflected light.

This work presents an optical pixel sensor to sense the blue light input signal and suffers less interference from ambient light, as a compensating current is generated using photo TFTs that are incorporated with the other two primary color filters (red and green). Furthermore, the designed active

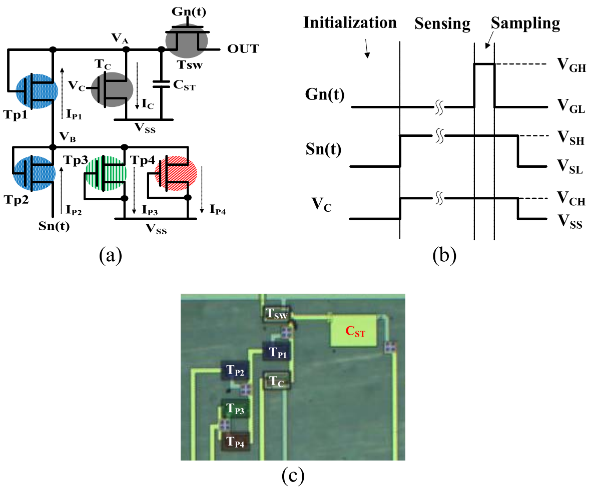

FIGURE 1. Proposed optical pixel sensor. (a) Schematic diagram. (b) Timing diagram. (c) Optical image.

load of the gate voltage is adjusted, making the proposed optical sensor generate a modifying current to counteract the photocurrent induced by the reflected light. The measured results demonstrate that the proposed optical pixel sensor suppresses the effects of ambient light with the intensity of up to 12560 lux and avoids false detection under the simulated reflected blue light with an intensity of 588 lux, verifying its high robustness against the effect of ambient light and reflected light.

II. SENSOR SCHEMATIC AND OPERATION

Fig. 1(a) and (b) display the schematic diagram and the timing diagram of the proposed optical pixel sensor. The proposed sensor consists of four photo TFTs (T_{P1}-T_{P4}), one switching TFT (T_{SW}), one controlling TFT (T_C), and one storage capacitor (C_{ST}). T_{P1} and T_{P2} are covered with blue filters to sense the principal sensing color. T_{P3} and T_{P4} are respectively covered with green and red filters to detect the intensities of green light and red light, respectively. T_{SW} and T_C are covered by a metal shielding layer which prevents the illuminant from altering their characteristics. The operation of the proposed optical sensor is divided into three periods, which are initialization, sensing, and sampling.

During the initialization period, Sn(t) is at V_{SL}, so T_{P1} and T_{P2} are turned on to reset the voltage of nodes A and B to $V_{SL} + V_{TH2} + V_{TH1}$ and $V_{SL} + V_{TH2}$, respectively, where V_{TH1} and V_{TH2} are the threshold voltages of T_{P1} and T_{P2}. During the sensing period, Sn(t) changes from V_{SL} to V_{SH} to turn off T_{P1} and T_{P2}, generating photocurrents of T_{P1} and T_{P2} (I_{P1} and I_{P2}) under illumination by blue light. T_{P3} and T_{P4} generate photocurrents (I_{P3} and I_{P4}), which sense green and red ambient light, respectively. Based on Kirchhoff's current law, at node B, $I_{P1} = I_{P2} - I_{P3} - I_{P4}$. When a sufficient blue light input signal illuminates the proposed sensor, I_{P2} is larger than the sum of I_{P3} and I_{P4}. Thus, node B is charged to a high voltage, and the photocurrent through T_{P1} (I_{P1}) increases the charges stored in C_{ST}. In contrast, under only illumination of ambient white light, the proposed sensor satisfies $I_{P3} + I_{P4} > I_{P2}$ since the sum of the channel widths of T_{P3} and T_{P4} is designed larger than that of T_{P2}. Consequently, even if strong ambient light activates T_{P2} to generate a photocurrent, then T_{P3} and T_{P4} generate a compensating current to keep node B at a low voltage, making the proposed sensor highly reliable under strong ambient light. Notably, when reflected light from the hands of a user illuminates other sensors, T_{P1} and T_{P2} generate photocurrents (I_{P1} and I_{P2}) that charge nodes A and B. Simultaneously, the active load (T_C) is biased by the designed voltage V_{CH}, which can be adjusted beforehand, based on the worst-case intensity of reflected light, generating a modifying current (I_C) to counteract the photocurrent that is induced by reflected light. Thus, the proposed optical sensor prevents an increment of charges that is stored in C_{ST} under low-intensity blue light. During the sampling period, Gn(t) switches from V_{GL} to V_{GH}, so T_{SW} is turned on to deliver the voltage of node A to an external charge amplifier to detect the result of sensing. With the proposed sensor design, the compensating current effectively suppresses the effect of ambient light, and the active load generates a modifying current that prevents the proposed sensor from reacting to low-intensity blue light.

III. MEASURED RESULTS AND DISCUSSION

Fig. 1(c) displays an optical image of the top of the proposed sensor that is fabricated using the standard a-Si:H TFT process. To compare the performance of the conventional sensor [7], previously developed work [8], and the proposed sensor, all three optical sensors are fabricated with the same device parameters. The ratios of the channel widths to lengths of the photo TFTs (T_{P1}-T_{P4}) and the switching TFT (T_{SW}) of the sensors are 60/8 μm/μm and 60/6 μm/μm, respectively. That of the controlling TFTs (T_C) in the proposed sensor is 80/8 μm/μm. The storage capacitor (C_{ST}) used in the sensors has a capacitance of 3 pF, and the V_{CH} and V_{SS} that are applied to the proposed sensor are set to -6.3 V and -10 V, respectively. The voltage swings of signal Gn(t) and Sn(t) are -10 V to 25 V and -10 V to 15 V, respectively. The durations of the initialization period, the sensing period, and the sampling period are set to 40 μs, 10.3 ms, and 300 μs, respectively. The intensities of the blue light input signal and the simulated reflected light are set to 2538 lux and 588 lux, respectively. Notably, all three sensors incorporate with an inverter [9] to prevent the oscilloscope probe from interfering with the sensing results when the voltage of node A is measured. Fig. 2 plots the measured output transfer curve of the readout circuit, exhibiting a sufficiently wide non-saturated region between -5 V and 15 V to sample the voltage of node A.

To verify the stability of the proposed sensor under varying ambient light, Fig. 3 plots the measured waveforms of the conventional sensor and the proposed sensor under ambient

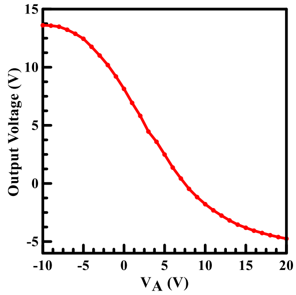

FIGURE 2. Measured output transfer curve of readout circuit.

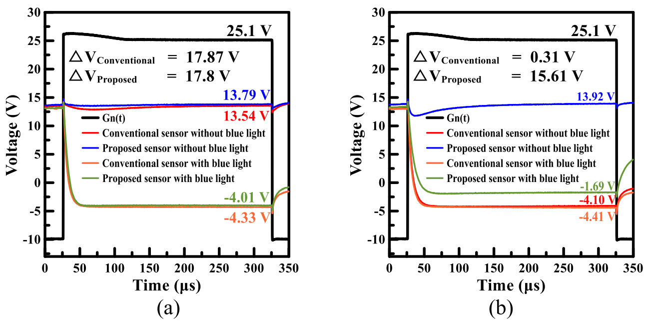

FIGURE 3. Measured waveform of output voltage of sensor under ambient white light intensity of (a) 778 lux and (b) 12560 lux.

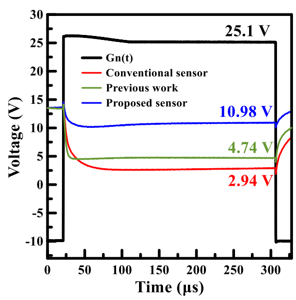

FIGURE 4. Measured output voltages of sensors under blue light intensity of 588 lux.

white light with the intensities of 778 lux and 12560 lux with/without blue light with an intensity of 2538 lux. Both optical sensors sense whether the blue light input signal of 2538 lux is present under ambient white light with an intensity of 778 lux, as shown in Fig. 3(a). However, under ambient white light with an intensity of 12560 lux, the conventional sensor is at -4.1 V without blue light, leading to false detection. In contrast, the proposed sensor is at -1.69 V and 13.92 V with and without illumination of blue light, maintaining high SNR under ambient light with an intensity of 12560 lux, as shown in Fig. 3(b). To demonstrate further the reliability of the proposed sensor under illumination by reflected light, Fig. 4 plots the measured output waveforms of the conventional sensor, the previously developed work, and the proposed sensor under blue light with an intensity of 588 lux. The output voltages of the conventional sensor and the previously developed sensor are reduced to 2.94 V and 4.74 V, respectively. In contrast, since I_C suppresses the

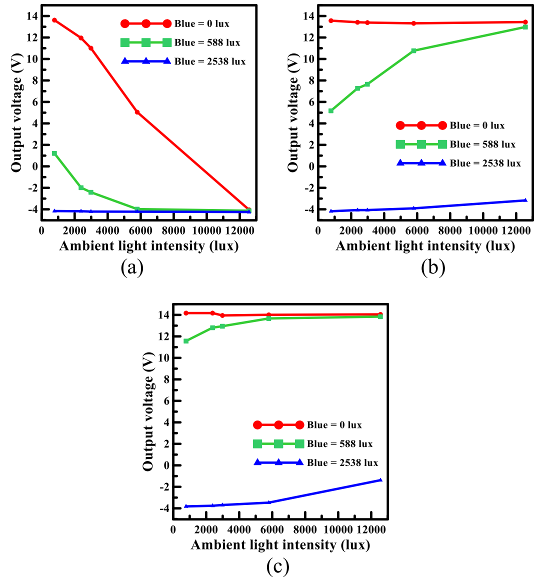

FIGURE 5. Measured output voltages of various optical sensors. (a) Conventional sensor. (b) Previously developed work. (c) Proposed sensor.

photocurrent that is induced by reflected light, the output voltage of the proposed circuit is maintained at a high level of 10.98 V, demonstrating its immunity to the reflected light. Fig. 5 plots the measured output voltages of three sensors in blue light with the intensities of 0 lux, 588 lux, or 2538 lux under ambient white lights of various intensities. The output voltage of the conventional sensor decreases to -4.05 V under ambient white light with an intensity of 12560 lux, and the SNR of the conventional sensor is significantly narrowed, resulting in false detection, as shown in Fig. 5(a). Fig. 5(b) plots the output voltage of the previously developed sensor, which can maintain a high SNR under ambient white light with an intensity of 12560 lux. However, the previously developed sensor exhibits interference in the blue light with an intensity of 588 lux, leading to an unfavorable SNR under ambient white light with an intensity of less than of 5790 lux. In contrast, the proposed sensor exhibits a high SNR under blue light with an intensity of 588 lux since the modifying current mitigates the photocurrent induced by reflected light, as shown in Fig. 5(c). Notably, the output voltage of the proposed circuit slightly increases under blue light with an intensity of 2538 lux and strong ambient light. Nevertheless, the SNR of proposed sensor still suffices to enable it to detect the blue light input signal herein. Therefore, by sensing optical signal of a specified color under high ambient illumination and meanwhile allowing a finger touching on whole panel without any false detection, the proposed optical sensor can provide a more comfortable user experience in pen-writing interactive applications.

IV. CONCLUSION

This work presents an optical pixel sensor comprising three photo TFTs with RGB primary color filters to compensate for the ambient light effect. Moreover, an active load is added into the structure to ameliorate the reflected light effect. The experimental results herein demonstrate that the proposed optical sensor has a favorable SNR in ambient light with an intensity of 12560 lux, avoiding false detection under the reflected light with an intensity of 588 lux. Thus, the proposed optical sensor is highly promising for integration in LED pen-writing interactive whiteboards and large displays.

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