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Integrated Ambient Light Sensor with an LTPS Noise-Robust Circuit and a-Si Photodiodes for AMLCDs

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SUMMARY Ambient light sensors have been used to reduce power consumption of Active Matrix Liquid Crystal Displays (AMLCD) adjusting display brightness depending on ambient illumination. Discrete sensors have been commonly used for this purpose. They make module design complex. Therefore it has been required to integrate the sensors on the display panels for solving the issue. So far, many kinds of integrated sensors have been developed using Amorphous Silicon (a-Si) technology or Low Temperature Polycrystalline Silicon (LTPS) technology. These conventional integrated sensors have two problems. One is that LTPS sensors have less dynamic range due to the less photosensitivity of LTPS photodiodes. The other is that both the LTPS and a-Si sensors are susceptible to display driving noises. In this paper, we introduce a novel integrated sensor using both LTPS and a-Si technologies, which can solve these problems. It consists of vertical a-Si Schottky photodiodes and an LTPS differential converter circuit. The a-Si photodiodes have much higher photosensitivity than LTPS ones, and this contributes to wide dynamic range and high accuracy. The LTPS differential converter circuit converts photocurrent of the photodiodes to a robust digital signal. In addition it has a function of canceling the influences of the display driving noises. With the circuit, the sensor can stably and accurately work even under the noises. The performance of the sensor introduced in this paper was measured to verify the advantages of the novel design. The measurement result showed that it worked in a wide ambient illuminance range of 5–55,000 lux with small errors of below 5%. It was also verified that it stably and accurately worked even under the display driving noise. Thus the sensor introduced in this paper achieved the wide dynamic range and noise robustness.
key words: *ambient light senor, a-Si photodiodes, LTPS circuit, wide dynamic range, noise-robustness*

1. Introduction

Reducing AMLCD's power consumption is particularly required in mobile applications such as mobile phone. One method for lowering the power consumption is to adjust backlight brightness of an AMLCD module depending on ambient illumination. Under the condition of low ambient illuminance, the backlight brightness can be lowered for reducing the power consumption without impediment to display's readability.

Today the ambient light sensing systems usually use discrete sensors. But the display modules which have the discrete sensors tend to become rather complex and have mechanical limitations. In order to avoid them, several techniques of integrating an ambient light sensor on a display panel were developed by use of a-Si technology or LTPS technology [1]–[7].

Integrated sensors in a-Si technology, which consist of a-Si photodiodes without integrated circuits, have an advantage of high photosensitivity of a-Si photodiodes. However, they have an issue of less noise robustness because their photocurrents on the interconnections between the photodiodes and a control IC are susceptible to electrical and/or electromagnetic noises coming from display driving components.

On the other hand, integrated sensors in LTPS technology have a feature of having an integrated LTPS circuit as well as LTPS photodiodes. The circuit converts the photocurrent of the photodiode into a signal such as an analogue voltage level or a digital pulse, enabling better noise robustness and module design simplification. However the noise effect can't be completely eliminated even with the circuit. In addition, the photosensitivity of the LTPS photodiodes is so low that it is difficult to achieve a wide dynamic range and high accuracy of the ambient light sensing.

We used an ambient light sensor integrated into an AMLCD with both the a-Si and LTPS technologies. It enables an accurate sensing in a wide ambient illuminance

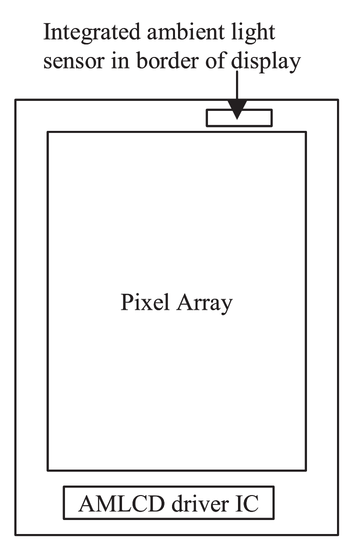

Fig. 1 Display with an integrated ambient light sensor.

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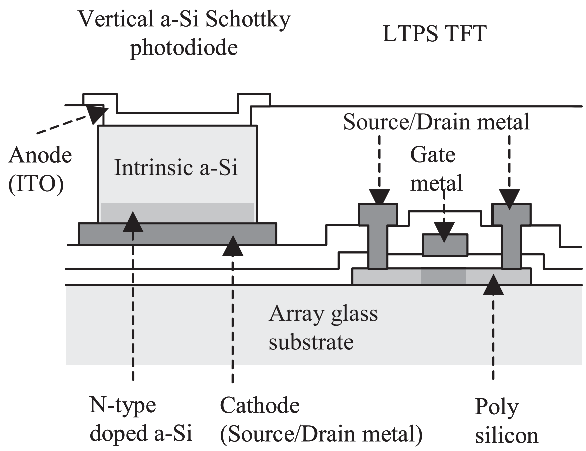


Fig. 2 Structure of vertical a-Si Schottky photodiode.

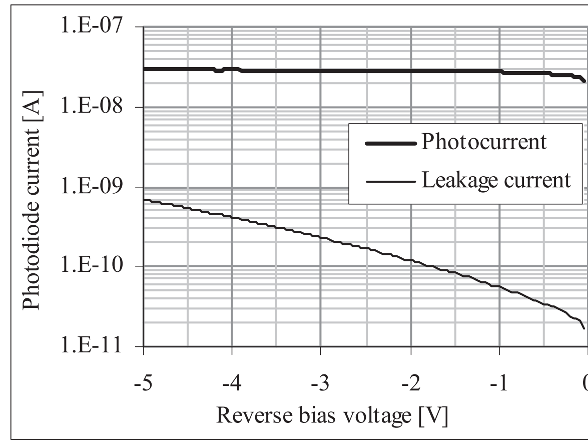


Fig. 3 Measured characteristic of a-Si Schottky photodiode.

range even under a noise in the mobile display applications. The sensor consists of vertical a-Si Schottky photodiodes and an LTPS noise-robust circuit that converts the photocurrent of the photodiodes into a digital signal. Then, the signal is supplied to the display brightness controller.

The sensor is located close to the pixel array area of the display and in the border region as shown in Fig. 1. This layout doesn't need additional apertures or optical components for the ambient light sensing system to guide the ambient light to the sensor while the discrete sensors require them.

2. a-Si Photodiode Structure and Characteristic

The structure of the vertical a-Si Schottky photodiodes is shown in Fig. 2. The a-Si photodiode is made on LTPS Thin Film Transistor (TFT) array substrate. A cathode electrode is made during making data lines of the display. Then N-type doped and intrinsic a-Si layers are deposited on the electrode. Transparent ITO that passes the ambient light coming from topside is used for making an anode electrode on the intrinsic a-Si layer. Thus, both the a-Si photodiodes and LTPS TFTs can be made on the same array substrate. Similarly combined poly-Si-TFT-a-Si-photosensor structure has been used previously for image sensors applications [8], but in the current approach, we have used the ITO optical window layer as also a Schottky contact to a-Si. Discussion of I-V characteristics of ITO-a-Si contact can be found in our earlier publication [9]. The use of ITO as the Schottky contact has advantages of process simplification since no additional contact layer or doping process is needed and the Schottky contact layer can be simultaneously formed during pixel ITO formation. Thus the vertical photodiode can be integrated in to TFT array process by only one additional deposition (N+-a-Si/a-Si continuous deposition) and patterning processes. An additional contact layer (such as P+ a-Si) between a-Si and ITO leads to reduction in quantum efficiency due to absorption of light in the contact layer as can be seen in our previous work [9].

The a-Si photodiodes have several orders of magnitude higher photosensitivity than the LTPS photodiodes. The photodiodes have a photocurrent generated by the ambient light, and have a leakage current, which flows with reverse bias voltage applied. Figure 3 shows the measured photocurrent and leakage current of the a-Si photodiodes. The a-Si photodiodes on a bare array substrate glass is illuminated with a halogen light source of 330 lux at a temperature of 25 degrees C. The horizontal axis shows reverse bias voltage level applied to the a-Si photodiode, and the vertical axis shows the measured photocurrent and leakage current. The photocurrent is much larger than the leakage current, and the characteristic of the a-Si photodiodes allows accurate ambient light sensing even under low ambient illuminance where it is difficult for the LTPS photodiodes to do that. In addition, the cathode electrode metal under the N-type doped a-Si layers work as a backlight shield, which can significantly reduce an influence of a backlight on the accurate ambient light sensing in AMLCDs.

In order to integrate lateral LTPS PIN diodes into a top-gate TFT array, additional mask processes are needed to form backlight-shield structure and to mask the i-layer of the PIN photodiodes during LDD doping process, whereas only one additional mask process is needed to integrate the a-Si photodiodes.

3. Architecture of Ambient Light Sensor

The architecture of the sensor introduced in this paper, which was implemented on a display, is shown in Fig. 4. It consists of four equal-size a-Si photodiodes (E_1, M_1, M_2 and M_3) and an LTPS differential converter circuit.

E_1 is exposed to the ambient light while M_1, M_2 and M_3 are masked with a black matrix layer of a color filter glass sheet for shielding the ambient light. E_1 has both the photocurrent and leakage current. On the other hand, currents passing through the masked photodiodes are the leakage current.

The leakage current causes errors of the ambient light sensing especially under low ambient illuminance where the photocurrent decreases or under high temperature where the leakage current increases. Although the a-Si photodiodes

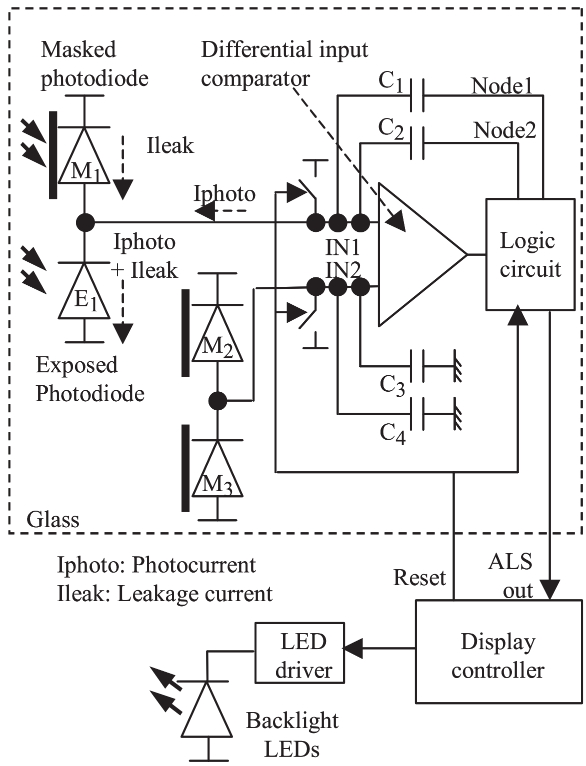


Fig. 4 Architecture of ambient light sensor and backlight control system.

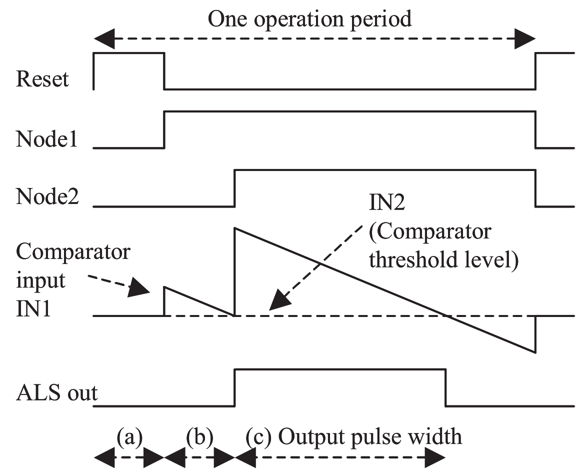


Fig. 5 Timing diagram of ambient light sensor operation.

have large photocurrent and relatively small leakage current, the leakage current influence needs to be further reduced in order to achieve higher accuracy of the sensing. The leakage current is subtracted by the series connection of the exposed photodiode E_1 and the masked one M_1 because they are designed to have the same leakage current and their leakage currents are compensated at the connection node of E_1 and M_1. Then, only the photocurrent generated by E_1 flows into an input (IN1) of the differential converter circuit. Thus the leakage current influence can be eliminated in this architecture. The other series connection of the masked photodiodes M_2 and M_3 having the same arrangement as E_1 and M_1 keeps a constant reference voltage for the other input (IN2) of that.

The differential converter circuit is also integrated on the TFT array substrate using the LTPS technology. The circuit converts the photocurrent into a robust digital output signal. The output of the circuit (ALS out) is connected to the display controller to control the backlight brightness as a function of ambient illumination.

The differential converter circuit has a differential input comparator that compares the voltage levels at IN1 and IN2. The output of the comparator is connected to the logic circuit which consists of logic gates and latch circuit. As a function of the control signal (Reset) from the display controller and the comparator output, the logic circuit produces pulse signals at Node1 and Node2 for generating charge injections at the comparator input IN1 through capacitors C_1 and C_2. Also it produces the sensor output (ALS out). Capacitors C_3 and C_4 are connected to IN2, and the other terminal of them is grounded. The circuit operation is controlled by Reset signal which initializes the circuit state.

As described above, IN1 has the flow of the photocurrent which discharges IN1 during the sensor operation. Meanwhile, there is no current flow at IN2 and then that is kept at a constant voltage. The voltage of IN2 is used as a threshold level of the comparator.

The timing diagram of the sensor introduced in the paper is shown in Fig. 5. The sensor operation is composed of three periods. In the first period (a), by the control signal of Reset, the logic circuit state is initialized, and IN1 and IN2 are biased to a reference voltage level. At the beginning of the period (b), by state change of Reset signal, the logic circuit makes a charge injection at the comparator input IN1 through the capacitor C_1. Then, the photocurrent discharges the injected charge at IN1 in the rest of (b) while there is no discharging or charging at IN2. When the voltage level at IN1 reaches IN2 level, it goes to the next period (c). At the beginning of the period (c), the logic circuit produces another charge injection through C_2 according to the state change of the comparator output. Then, the injected charge at IN1 is discharged again by the photocurrent. Thus the charge injection and discharging are done twice in the period of (b) and (c). While the period (b) is for canceling an offset error of the circuit, in the period (c) the circuit produces the digital output signal at ALS out, which has a pulse width that is equal to the time used for the discharging. The pulse width represents the photocurrent value as shown in Eq. (1) where Iphoto is the photocurrent value and V_{DD} is power supply voltage of the logic circuit. The display controller measures the pulse width in order to control the backlight brightness depending on the sensing result of the ambient illumination.

$$\textit{Output pulse width} = \frac{V_{DD} \cdot C_2}{Iphoto} \tag{1}$$

As shown on the timing diagram, the maximum voltage swing level of the comparator input during generating the output pulse is equal to the charge injection level, and it is independent of the input current from the photodiodes. This means the differential input comparator can be operated with small input voltage swing by using proper capacitance value of C_1 and C_2. Therefore high accuracy can be achieved in a wide range of ambient illumination because the comparator works with small input voltage range in which it has good linearity.

4. Noise-Robustness

Generally, operations of integrated ambient light sensors are affected by electrical and/or electromagnetic noises coming from other elements around the sensor such as a coupling from the common electrode of AMLCD with a line inversion driving scheme, noises from display driver and controller. Because the sensing electrodes of the photodiodes and the input of the converter circuits are high impedance and are located close to the noise sources. This results in less sensing accuracy or, in the worst case, malfunction of the sensors.

The key advantage of the sensor introduced in this paper is more noise-robustness. As described above, that has the symmetrical pair of the photodiodes and capacitors, which receive the noises of the same magnitude. By the differential input comparator, the noises applied equally to the pair can be theoretically eliminated because they are common mode noises and the differential input structure can cancel them as is well known. Thus the architecture enables stable and accurate sensing even under the noises.

5. Results and Discussions

Measurements made by the sensor introduced in this paper are shown in Fig. 6. The sensor on the display module is illuminated with a halogen light source at room temperature, and the horizontal axis shows the light intensity in lux. The vertical axis represents the output of the sensor in arbitrary units, and the graph shows the inverse of the output pulse width of the sensor. Figure 7 shows the measured linearity errors of the outputs. The definition of the linearity error is shown on Eq. (2) in which Output means the inverse of the output pulse width.

$$\textit{Linearity error at Xlux} = \left\{ \frac{(\textit{Output at Xlux}) \cdot 1000}{(\textit{Output at } 1000\,\textit{lux}) \cdot X} - 1 \right\} \cdot 100\,[\%] \quad (2)$$

The outputs of all the measured samples have a linear dependence on the ambient illuminance, and the errors are below 5% over the wide ambient illuminance range from 5 to 55,000 lux. Thus we have successfully verified the performance that can be achieved with the high photosensitivity of the a-Si photodiodes and the architecture.

Figure 8 shows a measurement result of the temperature dependence of the sensor introduced in this paper. The horizontal axis shows temperature, and the vertical axis shows the change in the sensor output from 25 degrees C. The definition is shown on Eq. (3) in which Output means the inverse of the output pulse width.

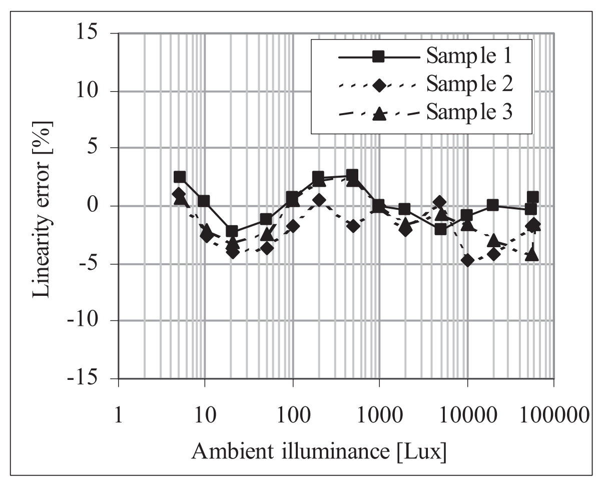


Fig. 7 Measurement result of linearity error of ambient light sensor.

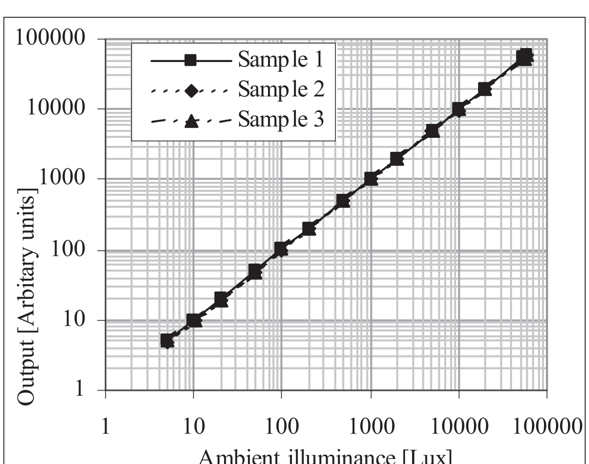


Fig. 6 Measurement result of ambient light sensor output.

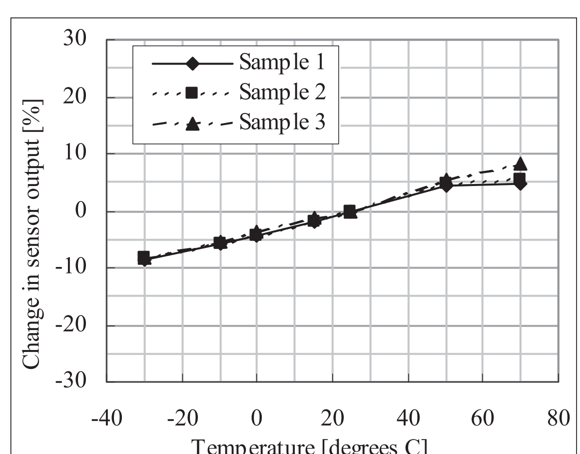


Fig. 8 Measurement result of temperature dependence of ambient light sensor output.

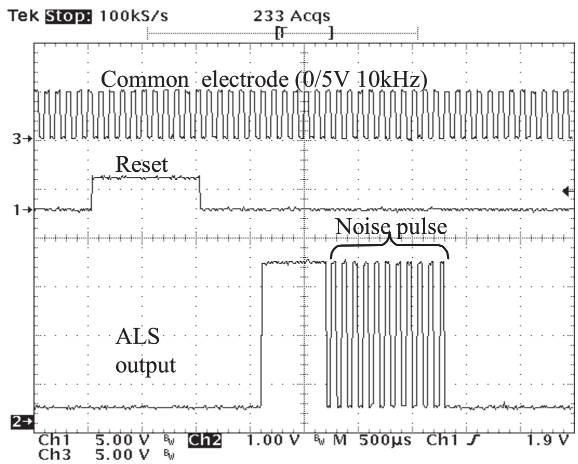


Fig. 9 Measured waveforms of an ambient light sensor of a prior technique.

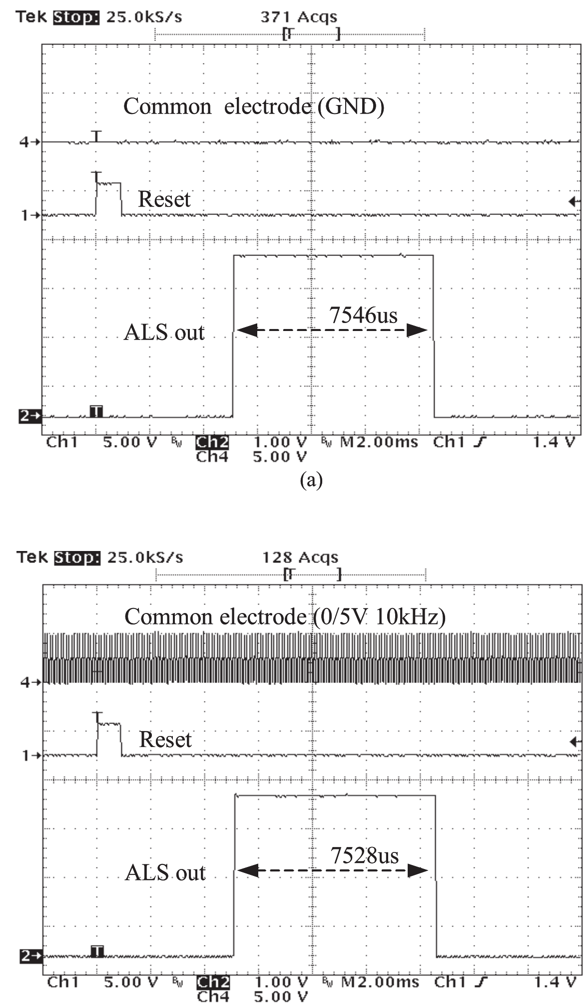
$$\textit{Change in sensor output} = \left(\frac{\textit{Output at } X \deg C}{\textit{Output at } 25 \deg C} - 1\right) \cdot 100\,[\%] \qquad (3)$$

The sensor is operated under ambient illuminance of 100 lux. The dependence on the temperature is less than 10% from −30 to 70 degrees C. The a-Si photodiodes with the leakage current subtraction contribute to the small dependence on the temperature, and enable accurate operation under a variable temperature condition of the mobile display applications.

In order to confirm the effect of the noise-robust design, we have also verified the sensor operation with a coupling noise from the common electrode of AMLCD.

For comparison, an integrated sensor of a prior technique [3] that we published previously was measured. It consists of LTPS photodiodes and an LTPS converter circuit, and the circuit controlled by a signal (Reset) produces a digital output signal (ALS output). Its basic operation is similar to the sensor introduced in this paper, however it doesn't have noise canceling function. The sensor of the prior technique is operated with a noise induced by common electrode alternation like a line inversion driving scheme of AMLCD, and the measured waveforms are shown in Fig. 9. The sensor operation is affected by the noise, and the output has unexpected noise pulses. This results in a malfunction of the ambient light sensing system.

The measurement results of the sensor introduced in this paper are shown in Fig. 10. The waveforms on (a) are without the noise, and those on (b) are with the same noise as described above. Consequently there is little difference of the output values between these conditions, and the output noise pulse or malfunction is not seen even with the noise. Thus, the differential converter circuit and symmetrical pair of the a-Si photodiodes work well and are effective in canceling the noise, and then the noise robustness is significantly improved.



(b)

Fig. 10 Measured waveforms of the ambient light sensor introduced in this paper (a) without noise and (b) with coupling noise from common electrode.

6. Conclusion

We have developed the ambient light sensor integrated into AMLCD with both the a-Si and LTPS process technologies. Compared to the prior techniques, this sensor has higher photosensitivity. In addition, the combination of the a-Si photodiodes and integrated LTPS converter circuit which has the differential input allows stable and accurate operation of the ambient light sensing even under noisy circumstances. The measurement results show its capability of detecting the ambient illuminance from 5 to 55,000 lux with below 5% error. Compared to LTPS sensors that need some extra masks for LTPS photodiodes, the sensor with a-Si photodiodes doesn't have disadvantages of mask count and cost because only one additional is used for making the a-Si layers.

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