In-Cell Sensors for Light-Adaptive LCDs

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1. Abstract

In-cell sensor technology applied in Liquid Crystal Displays (LCDs) panels are investigated to enable adaptive adjustment of screen brightness and color temperature based on ambient light, thereby enhancing the display performance of screens in various environments. By incorporating ambient light sensors (ALS) and color temperature sensors (CTS), which are compatible with the normal manufacturing process of LCD panels, TCL CSOT has achieved a technological upgrade compared to traditional LCDs technology. In-cell ALS referred to a wide sensing range of 0~10000 lux and high resolution of 1 lux below 50 lux. In-cell CTS showed an effective range of 3500~9000 K with detection accuracy of 800 K. With these sensors, LCDs panel can adaptively change its brightness and color temperature within different environments, leading to a new feature of TV, monitor and other commercial LCDs.

2. Author Keywords

In-cell technology, Ambient light sensor, Color temperature sensor, Dynamic Invocation

3. Introduction

Televisions are among the most widely owned devices in households, with significant energy consumption. According to the U.S. Department of Energy, American TV sets consume around 65 billion kilowatt-hours of energy annually, accounting for 4-5% of household electricity use. As thin-film transistor (TFT) liquid crystal displays (LCDs) evolve towards higher resolutions, faster response times, and larger panel sizes, the power consumption of the displays also increases. One of the primary sources of power consumption in LCDs is the backlight. The adaptive brightness function in LCDs aims to reduce power consumption by dynamically adjusting the screen's brightness according to ambient light conditions.

Another important topic is eye-comfort and visual healthiness. The human visual system is highly sensitive to changes in light conditions. Adaptive brightness and color temperature features allow screens to adjust their display effects automatically and maintain a comfortable visual experience. This is particularly important for users who engage with display devices for extended periods, as appropriate brightness and color temperature settings can reduce eye strain and visual discomfort.

Beyond brightness and color temperature concerns, motion blur artifacts significantly impact LCDs, especially during fast-paced scenes and at lower temperatures.

Ambient light sensors (ALS) and color temperature sensors (CTS) have been integrated into LCDs to enhance user experience. However, these sensors require additional modules and an aperture for light transmission, and that increases the display module's complexity. Moreover, large-sized LCDs like TVs and monitors need multiple sensing positions to avoid failure of ALS and CTS due to light block by users or objects, making them incompatible with these supplementary sensor modules.

Therein, upgraded in-cell sensors are developed by CSOT to solve these problems, providing a prospective feature of automatic adjustments of screen brightness and color temperature. Users can achieve a more comfortable visual experience across different settings, along with energy conservation. In-cell integrated ALS and CTS displays do not require module openings, making them more suitable for full-screen and narrow-border displays. Multiple sensors (three or more) can be integrated within the screen, addressing the current pain-point of single commercial light sensor modules that are easy to be blocked. Furthermore, sensors are compatible to normal TFT-LCDs structure without any additional mask for processes. Incell sensor technology can be widely applicable across various scenarios in prospect, including Notebooks, Monitors, and TVs.

4. Method

In-cell ALS made by a-Si process: We proposed an integrated ambient light sensor using normal a-Si process. The in-cell ALS as a-Si photosensitive resistance device can be embedded in array-TFT. Cross-section schematics of the a-Si semiconductor photosensor integration are illustrated in **Fig. 1**. ALSs were integrated into a Back-Channel-Etching (BCE) process with no additional mask in LCDs process. Photosensitive resistance was mainly attributed by a-Si, which is connected between source and drain electrode in the TFT-like device. The gate electrode served as a light shield layer to prevent the interference of backlight, so it was always floating in electric connection to make sure of that being a photoresistor but not a TFT.

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An aperture for light above the device was made by BM (Black Matrix) layer. Usually, the size of aperture, which could be designed by case, was a bit larger than a-Si area to make sure the back-channel of a-Si could accept the light from out-cell. But the aperture shall not be too large to prevent visuality, because source and drain electrodes, which were made by metal layer, could be seen due to the different reflectivity of metal and BM.

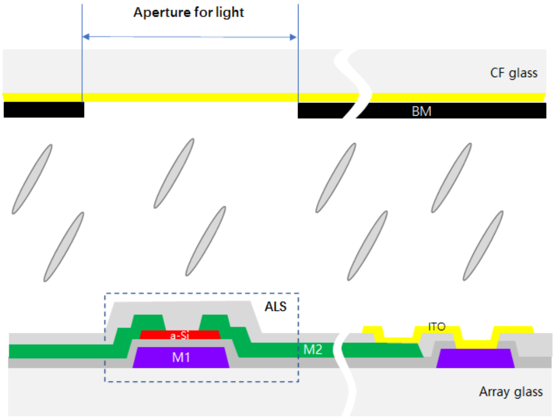

Figure 1. Cross-section schematic of In-Cell a-Si ALS integration in LCDs

In-cell CTS made by a-Si process: The structure and design of in-cell CTS was similar to those of ALS. Both COA (color filter on Array, **Fig. 2a**) and non-COA (**Fig. 2b**) structures are applicative. The CTS, which is constructed with an a-Si device, is primarily tasked with detecting small differences in color ratios that result from varying color temperature. The conventional approach to detect the small differences is to involve measuring with sensors and corresponding color filters, and computing the actual light intensities of at least three distinct colors, such as blue, red, and green. By this method, the precision of color temperature sensors is decided by absolute accuracy and accuracy of the sensors and color purity of filters. While this method is suitable for PIN photodiodes as sensors, it is generally not ideal for the production of large-scale LCD panels such as those used in TVs and monitors. The incorporation of PIN photodiodes into standard LCDs necessitates additional masking and processing steps, which in turn escalate the manufacturing costs. Photoresistor sensor devices, on the other hand, fit perfectly to existing LCD production process. However, they exhibit a limitation in sensitivity when it comes to detecting little changes in individual colors across varying color temperatures.

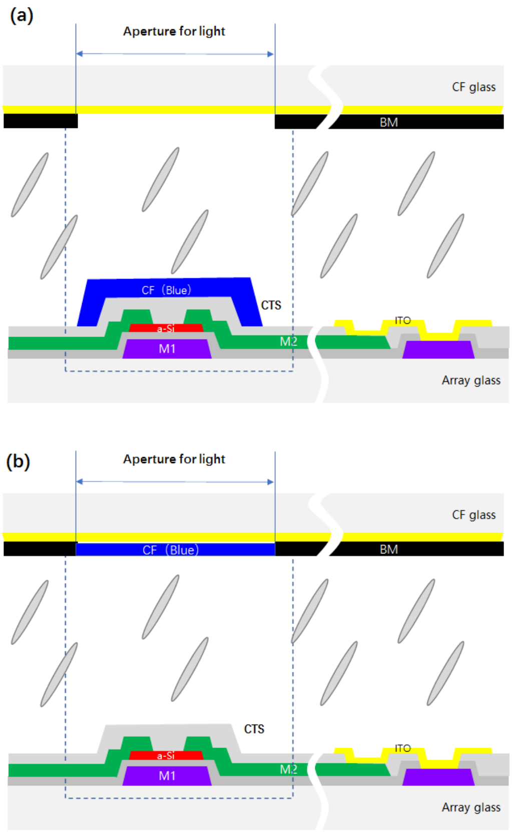

Figure 2. Cross-section schematics of In-Cell a-Si CTS (blue) integration in LCDs: (a) COA structure, (b) non-COA structure.

We introduced a novel approach to detecting color temperature using in-cell photoresistor sensors, which is based on the comparative analysis of individual colors. As the color temperature shifts towards the cooler end, the intensity of blue light increases while that of red light decreases. Conversely, when the light becomes warmer, blueness decreases along with the redness rises. Although the absolute changes in intensity are minor, the ratio of the color intensities is significantly greater, leading to easier readout and calculation. For example, the light becomes warmer, with the intensity of blueness changes from 1000 to 990 while redness from 1000 to 1010 (numbers are hypothetical for illustrative purposes). The rate is only 1% for single color. When it comes to comparative ways, the ratio comes from 1000/1000=1 to 990/1010=0.98, meaning that the amplified rate of change is 2%.

Driving circuit of in-cell ALS and CTS: The driving circuit played a crucial role in driving and detecting the data of ALS and CTS. The classic circuit for reading a variable resistor is a voltage divider circuit. By this method, we could readout the photosensitive resistance of a-Si device easily. Basic circuit model for ALS is shown on **Fig.3**, turning the resistance into voltage. R_p corresponds to photosensitive resistance in ALS, and R_c is the matching fixed resistor. The readout results can be calculated by equation (1). VDD and VSS are constant voltage, while VSS is set GND as usual and VDD can be set by case.

$$V_{Readout} = \frac{R_p}{R_p+R_c}\cdot(VDD-VSS) \quad \cdots\cdots\cdots \ (1)$$

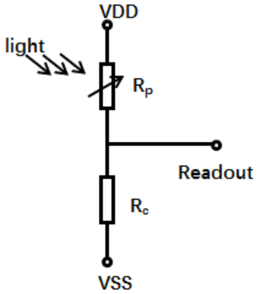

Figure 3. Circuit model for ALS

The driving circuit of CTS is similar to ALS, calculating the result of comparative of R_b, the photoresistor below blue CF and R_r, the photoresistor below red CF, which is depicted at **Fig, 4**. The CTS readout results can be calculated by equation (2).

$$V_{Readout} = \frac{R_b}{R_b+R_r}\cdot(VDD-VSS) \quad \cdots\cdots\cdots \ (2)$$

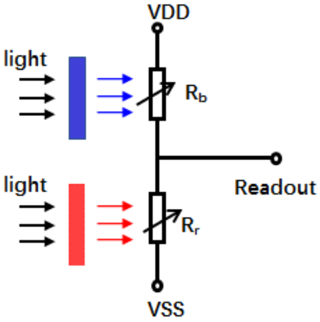

Figure 4. Circuit model for CTS

We tested an ALS, trying to get the relation of readout and incident light intensity. The test results of ALS are depicted at **Fig. 5**, showing the partial characteristic curve of readout data varied with light intensity from 0~900 lux, which can cover most of the indoor lighting range. In fact, the response can cover a range of 0~10000 lux. This curve with a nonlinear relationship indicates the ALS device is mainly photosensitive resistance. By a formula fitting method, we can easily infer the brightness from the readout based on the comparison relationship.

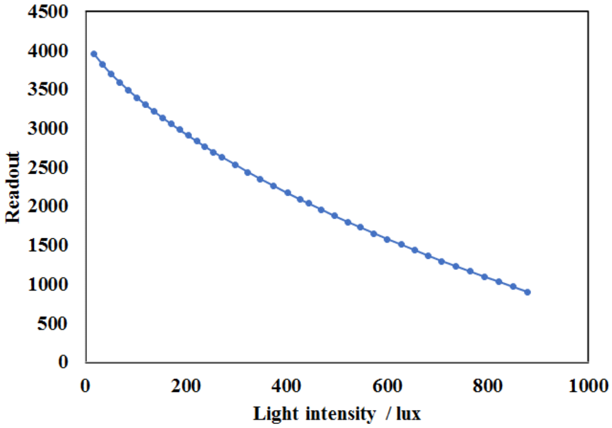

Figure 5. Readout-versus-light intensity curve of ALS (The readout data have been normalized)

Fig. 6 illustrates the readout versus color temperature curves of the CTS at specific light intensities. The curves corresponding to different light intensities are distinct and exhibit nonlinear characteristics. To deduce the color temperature of the surrounding environment, it is essential to first determine the light intensity as depicted in Fig 5. The individual fitting outcomes at various light intensities can be discerned from Fig 6. For example, 7 fitting formulas can be derived, each accompanied by a set of parameters within these equations. The parameters in groups can be further fitting to develop a method that generates a calculated curve or relationship, which is not tested and shown in Fig. 6 at the particular light intensity. By this new method, according to the readout of ALS and CTS, we can work backward to know the color temperature.

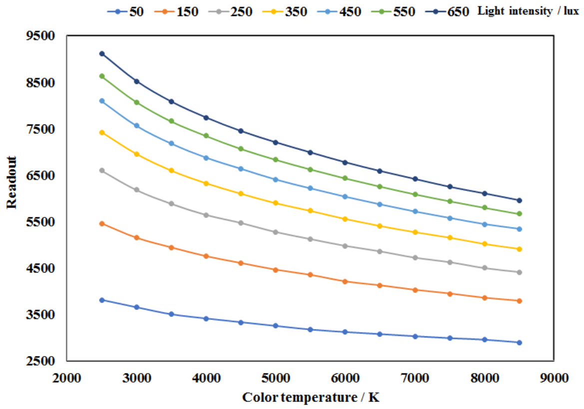

Figure 6. Readout-versus-color temperature curves of CTS (The readout data have been normalized)

5. System and prototype

All analog data were processed and converted into digital signals by the readout system and an Analog-to-Digital Converter (ADC) with 16 bits of resolution. Owing to the high resolution of the ADC, a high degree of sensing accuracy was achieved. In-cell ALS demonstrated a high resolution of 1 lux at levels below 50 lux, while in-cell CTS exhibited an effective range of 3500~9000 K with detection accuracy of 800 K.

Based on these sensors, a system for light adaptive LCDs could be designed. **Fig. 7** presents the functional schematic diagram of such a system. The digital data from the ADC is transmitted to a computing unit equipped with algorithms. The computed results are then fed back to modulate display characteristics, including brightness and color temperature. These feedback mechanisms can be customized to fit specific products and scenarios, thereby enhancing the user experience

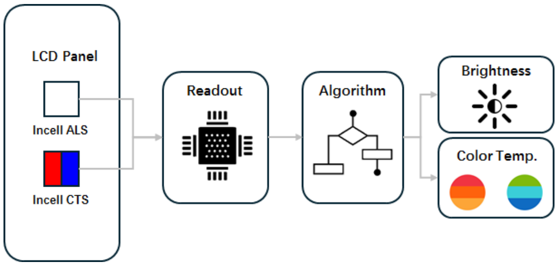

Figure 7. Functional schematic diagram of sensing and feedback system

A prototype (**Fig. 8**) driven by in-cell sensor technology was demonstrated at TCL CSOT Display Tech-ecosystem Conference (DTC) 2024, depicting the concept of light adaptive TVs.

Figure 8. Prototype of light adaptive TV (75")

6. Conclusion

In-cell sensor technology within LCD panels has been a subject of investigation to facilitate adaptive adjustments in screen brightness and color temperature. These adjustments are made in response to ambient light, with the aim of enhancing display performance across a variety of environments.

7. Acknowledgements

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8. References

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