Integration of Ambient Light Sensors in Pixel Circuit for Transparent Micro-LED Display Applications

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Abstract

Sensor integration in pixel circuits is emerging as an important development for transparent displays and automotive applications. This paper highlights the dual role of micro-LEDs as both light-emitting and ambient light-sensing elements. We propose a pixel driving method that enables micro-LEDs to both emit light and serve as ambient light sensors. Additionally, we demonstrate a 12.4-inch transparent display integrated with sensor-in-pixel functionality, with the aim of enhancing the adaptability of displays in diverse environmental conditions. This work paves the way for innovative developments in transparent display technology.

Author Keywords

Sensor integration; Ambient light sensor (ALS); photocurrent; micro-LED; pixel circuit; transparent display; automotive display

1. Introduction

With the increasing popularity of electric vehicles, transparent displays have become essential for various applications, such as head-up displays (HUD), car windows, sunroofs, and side windows on buses. Moreover, micron light-emitting diodes (micro-LEDs) have emerged as ideal devices for the next generation of displays due to their high brightness, contrast, high transparency, low power consumption, and long lifespan, thereby accelerating the development of transparent displays. In automotive applications, driver safety is always the top priority. Displayed information must be clear under all conditions, particularly in strong sunlight or dark tunnels. Typically, an ambient light sensor is mounted at the border of the display to adjust brightness. However, this sensor may be obstructed, preventing it from accurately sensing ambient light and responding promptly to changes in the display brightness. To address this limitation, some researchers have attempted to conceal multiple sensors beneath the pixel array. However, this approach faces challenges, such as decreased sensitivity to sunlight due to the sensors being positioned behind the substrate. Additionally, some pixel arrangements may need adjustment to accommodate the sensors, which can be visible to users and may affect the overall image quality of the display.

Consequently, embedding sensors in pixels has attracted growing attention for its potential to enhance in-time reaction and maintain display quality, while also saving costs associated with extra light sensors. Within each repeated unit pixel, there are typically two photosensitive devices: thin-film transistors (TFT) and micro-LEDs. Many studies have explored various TFT structures that respond to light [1]. In this paper, we propose using micro-LEDs to replace conventional ambient light sensors, as they are located on top of the substrate, making them closer to, and more sensitive to ambient light. Specifically, micro-LEDs in each pixel serve dual roles—both emitting light and sensing ambient light—and we present a pixel driving method along with read-out circuits designed for micro-LED sensing.

2. Micro-LED Characteristics and Sensing Mechanism

In display applications, micro-LEDs are typically operated at forward bias to emit light. Here, we wish to emphasize the intrinsic characteristics of LEDs: they are diodes consisting of p-type and n-type semiconductors that form a p-n junction. Under appropriate reverse bias voltage conditions, the LED can effectively detect incident light. When photons interact with the diode, electron-hole pairs are generated at the depletion region, resulting in the generation of photocurrent [2]. The quantity of electron-hole pairs produced is directly proportional to the intensity of the incident light. This dual functionality allows LEDs to serve effectively as both light emitters and sensors [3]. Indeed, conventional LEDs have been widely used in various applications for light emission and sensing [4][5]. Consequently, micro-LEDs present significant potential as ambient light sensors in display technologies.

The characteristics of red, green, and blue micro-LEDs are shown in Fig. 1 under various illumination conditions. The micro-LEDs array, consisting of around 700 dies connected in parallel, each have a size of less than 30 μm. The light source used for the experiments is a white LED light board, comprising several individual light bulbs measuring 0.5 mm × 0.5 mm each. In the reverse-bias region (i.e., when the voltage is less than 0V), micro-LEDs exhibit notable sensitivity to the ambient light conditions provided by the white LED light board, particularly the red micro-LEDs, whose generated photocurrent is nearly an order of magnitude greater than that of the green and blue counterparts. This variation in responsiveness can be attributed to the different wavelength sensitivities associated with each color of LED [6]. The red LED is particularly responsive to green and blue light, while the green LED primarily detects incident blue light. Conversely, the blue LED generally exhibits the lowest sensitivity to visible light, but it is often utilized for ultraviolet detection [7].

Table 1. Common Ambient Illuminance Values (Lux)

Environment	Illuminance (Lux)
Sunny	100,000
Cloudy	500~6000
Office	300~500
Tunnel	50~100
Street light	5
Full moon	0.2
Star light	0.0003

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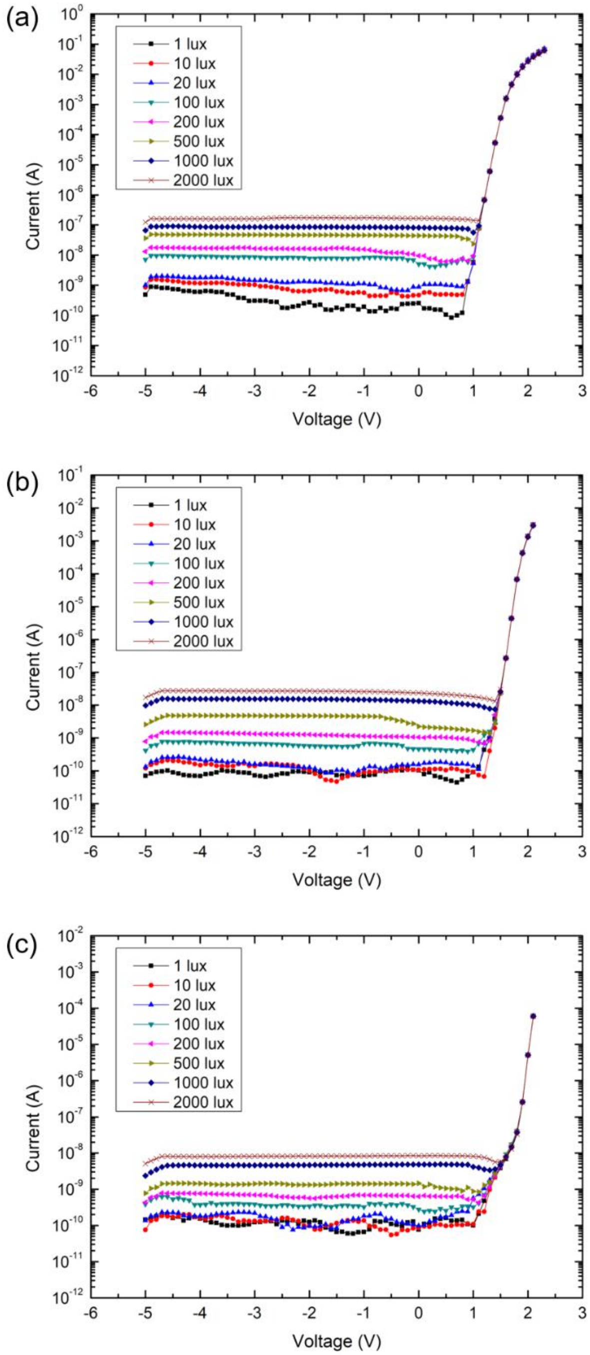

Figure 1. Characteristics of micro-LEDs: (a) red, (b) green, (c) blue.

To further explore this relationship, we present the correlation between photocurrent and the intensity of the ambient light source at a fixed reverse bias voltage of -4V in Fig. 2. The responsivity of the micro-LEDs is ranked from highest to lowest as follows: red, green, and blue. Additionally, the photocurrent generated by each type of micro-LED is found to be linearly correlated with the intensity of the incident light. The illuminance levels for various environments are provided in Table 1 for reference. The dashed line in Fig. 2 represents the linear fit of the data, with an R^2 value approaching 0.99. This characteristic holds considerable potential for applications in displays aimed at quantifying ambient light levels.

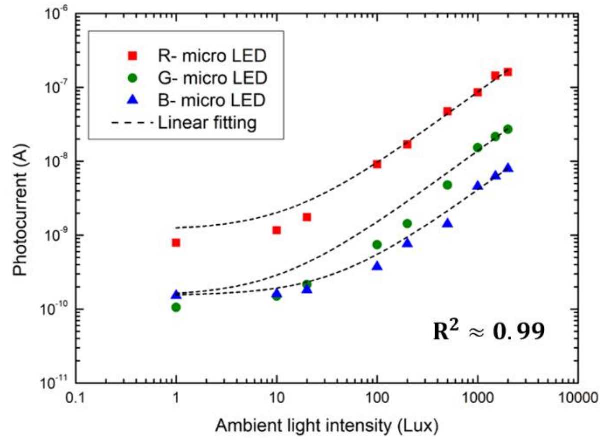

Figure 2. Linearity of photocurrent and ambient light intensity under a fixed reverse bias voltage of -4V.

3. Sensor-in-Pixel Circuit and System Design

Conventional pixel structures are designed as 2T1C or 6T1C configurations for current-driving of micro-LEDs [8][9]. We utilize the dual functions of micro-LEDs, proposing the configuration of a sensor-in-pixel circuit and its readout system in Fig. 3(a). The driving circuit shown here is composed of a 3T1C architecture for illustration, and it does not limit the framework to this architecture. T1 is used as a switch to write data to the gate of T2, while T2 drives the current for the micro-LED (M1) based on the written voltage. T3, controlled by the emission signal (EM), determines the timing for turning on M1. The storage capacitor, Cst, stabilizes the gate of T2, thereby stabilizing the output current and brightness. It is worth noting that in the readout circuit, we add T4 as a switch connecting the anode of M1 to the Vsens signal. The voltage of VSS is set higher than that of Vsens, causing M1 to operate in reverse-bias mode as a photosensitive device. This approach demonstrates that each pixel can function as an independent ambient light sensor. Additionally, through the repeated pixel units, the micro-LED sensing array is naturally formed, enhancing the signal-to-noise ratio (SNR) of the photocurrent. As shown in Fig. 3(b), the photocurrent collected from the active area is sent to a current-to-voltage converter (IVC), an analog-to-digital converter (ADC), and a microcontroller unit (MCU) of the IC. The converted digital code is referenced against a lookup table (LUT) to adjust the brightness of the panel.

It should be noted that in this driving approach, T3 and T4 cannot be turned on simultaneously. In other words, the signal waveforms of EM and SW has to be separated, as shown in Fig. 4. This design allows for flexibility in operation timing of micro-LEDs, determining when they are in emission mode and when they are in sensing mode. In Fig. 4(a), we can use the IC blanking time to sense ambient light while allocating the remaining frame time to emit the calibrated brightness. Furthermore, SW signal for T4 can also be controlled by the GOA signal, as shown in Fig. 4(b). This enables some horizontal lines in the panel to operate in emission mode, while simultaneously allowing other horizontal lines to function in sensing mode. Regardless of the driving approaches employed, a full-screen ambient light sensor-in-pixel configuration is achieved.

Last but not least, the readout circuit within the pixel can be integrated with additional functions, such as an anode reset circuit and an array testing circuit. The specifications of our transparent display with the sensor-in-pixel array are presented in Table 2. Several considerations for this driving method would be discussed in the next section.

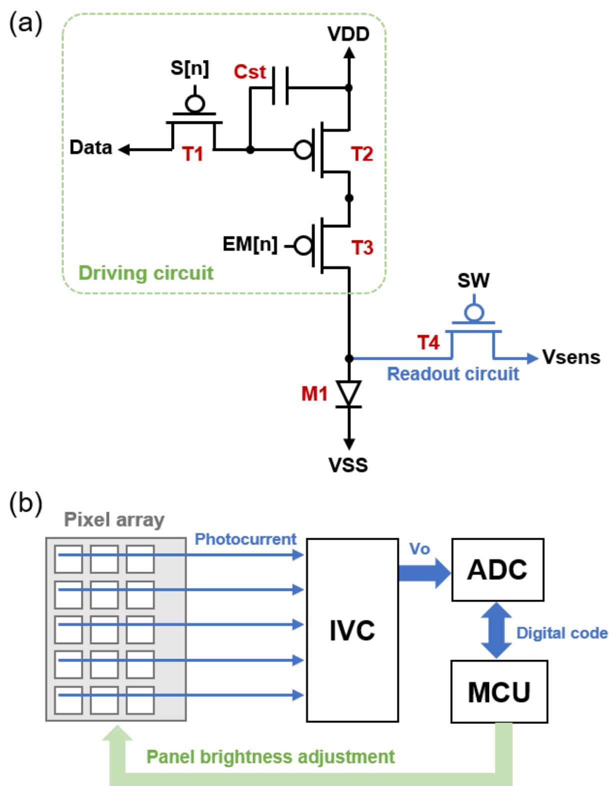

Figure 3. Schematics of (a) sensor-in-pixel circuit, and (b) photocurrent process flow.

Table 2. Transparent Display Specifications

Display size	12.4”
Pixel per inch (PPI)	93
Resolution (H×V)	360 × 1092 × RGB
Pixel size (μm)	274.5 × 274.5
Display type	LTPS Micro-LED
Border (μm)	170(T/L/R), 10000(B)
Transparency	60%
Frame rate (Hz)	60
Brightness (nit)	2000

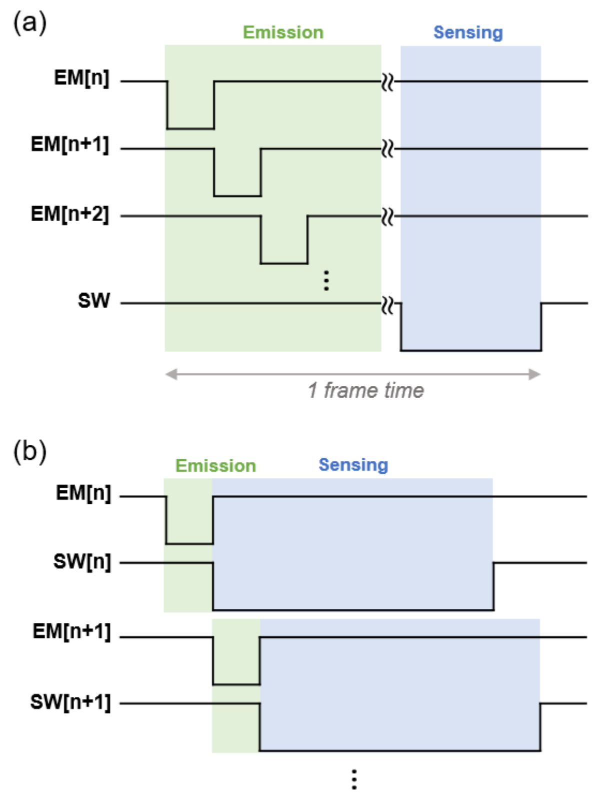

Figure 4. Timing chart of the sensor-in-pixel circuit: (a) Sensing mode during the IC blanking time; (b) SW control by the GOA signal.

4. Discussion

Before we proceed with the tape-out of the sensor-in-pixel layout, two main points need to be evaluated:

1. User Requirements

Given the wide range of illuminance values, from strong sunlight (approximately 10^5 lux) to dark night conditions (around 10^{-4} lux), as shown in Table 1, it is essential to understand the users' needs and the application environment at the start. Additionally, the current sensing resolution of the IC should be considered to calculate the minimum number of micro-LEDs required to sense light and provide sufficient photocurrent within the sensing interval. It is also important to take into account the differing linearity of photocurrent for the red, green, and blue micro-LEDs during these calculations. Furthermore, utilizing various current ranges or multiple gamma curves provided by the IC can facilitate the design of different sensing modes tailored to specific environments.

2. Brightness Adjustment

Once the analog photocurrent is converted into a digital code by the IC, several methods can be used in the micro-LED driving circuit to adjust brightness. These include modulating the written data voltage, adjusting the width of the emission (EM) signal—especially important for PWM driving—and varying the pulse count of the EM signal. Designers can choose the most suitable approach based on their specific circuit design requirements.

5. Conclusion

We utilize micro-LEDs within the pixel circuit as ambient light sensors and present a novel sensor-in-pixel driving method. The characteristics of micro-LEDs have been measured under various illumination conditions, ensuring the linearity of the photocurrent in relation to the intensity of ambient light. By appropriately separating the emission and sensing timing within the proposed pixel circuit, we eliminate the need for extra ambient light sensors hidden beneath the panel. This approach not only reduces costs but also preserves image quality. This work contributes to the ongoing development of transparent displays and automotive applications.

6. References

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