Optimization Design of Pixel Circuits to Drive the Innovative Micro LED Displays†

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Abstract

This paper presents a comprehensive comparison of panel specifications and performance quality (PQ), focusing on key metrics including full grayscale power consumption, pixels per inch (PPI), current error rates in low grayscale, and current pulse decay times. Additionally, we analyze various µLED driving methods, including Pulse Amplitude Modulation (PAM), Pulse Width Modulation (PWM), and Hybrid PWM Shared (HPS). The study also explores different pixel circuit designs, evaluating PAM, PWM, and HPS. A central theme of this discussion is the necessity and benefits of integrating hybrid driving approaches with stepwise waveform techniques, highlighting their potential to enhance display performance and usability.

Author Keywords

Micro-LED; PWM; pixel; Metal-Oxide TFT; IGZO

I. Introduction

The current state and future prospects of display technologies, specifically Organic Light Emitting Diodes (OLED) and Micro Light Emitting Diodes (µLED), present a fascinating landscape of innovation and opportunity. Over three decades of material and equipment development have led OLED technology [1] to become a common choice in smartphones and flexible televisions, showcasing its exceptional black display capabilities and sleek design. However, it faces challenges including burn-in effects and limited lifespan. On the other hand, µLED displays are gaining traction, particularly for applications requiring transparency and high brightness, with notable advancements in sunlight readability.

A comprehensive comparison reveals distinct characteristics between the two technologies. OLED utilizes organic compounds for self-emission, making its structure thin and flexible, while µLED is composed of tiny inorganic LEDs, boasting high brightness and longevity. OLED excels in delivering perfect blacks by allowing individual pixel shutdown, yet it is prone to burn-in issues [2]. Conversely, µLED offers superior brightness and resilience against burn-in, making it ideal for high dynamic range displays, with impressive color accuracy transcending both OLED and LCD.

In terms of dynamic range and contrast, OLED shines in HDR content; however, µLED's local dimming capability enhances its dynamic range without suffering from burn-in. Power consumption differs significantly, with OLED's consumption increasing at high brightness levels, while µLED maintains high efficiency and lower consumption across full-spectrum displays. Color performance is another stronghold, as OLED offers a wide color gamut but can exhibit color shifts with viewing angles, whereas µLED ensures better color stability and coverage regardless of angle.

When considering lifespan and durability, OLED's susceptibility to aging and high-temperature sensitivity [3] contrasts sharply with µLED's longer lifespan and environmental resilience. Cost remains a crucial factor; although OLED technology is established, high-quality models come at a premium, while µLED faces high production costs due to demanding material and manufacturing requirements.

In summary, despite OLED's maturity and widespread use in color accuracy and display quality, µLED stands out for its exceptional brightness, durability, and potential for transformative display applications. This article thoroughly examines the advantages and challenges facing these technologies, suggesting that µLED may become a mainstream choice in the future display market.

II. Pixel circuit design and uLED driving mode

In the field of uLED displays, various pixel designs can be employed to accommodate different application scenarios and display specifications. This section introduces three distinct operational modes of pixel circuits: PAM, PWM, and HPS.

As illustrated in Figure 1(a), the PAM circuit comprises a PAM control circuit and a light-emitting switch. Within this setup, the PAM control circuit undergoes a voltage reset via the Vref voltage, while the data voltage regulates the grayscale levels, with VDD and VSS supplying the necessary current. The operational emission mode of the PAM circuit is characterized by an emission duration that approaches 100% frame fixation, wherein the grayscale is determined by the magnitude of the driving current.

In contrast, the PWM circuit depicted in Figure 1(b) integrates a PWM control circuit in addition to the PAM control circuit and the light-emitting switch. This PWM control circuit determines the emission duration within a single frame and also utilizes a Vref_2 voltage reset to function, while PWM_Data determines the actual emission timing. Consequently, this structure allows for PAM_Data to influence the magnitude of the current pulse, while the PWM_Data dictates the width of this current pulse.

Finally, concerning the HPS circuit depicted in Figure 1(c), this arrangement features a PAM control circuit but differs from typical PWM circuits by allowing multiple PAM control circuits to share a common PWM control circuit.

Due to the absence of functionality for controlling current pulse width in the PAM circuit, it achieves a higher Pixels Per Inch (PPI) in the layout space. The PWM circuit that simultaneously controls the light emission duration and current magnitude through current pulse modulation (CPM) requires a greater number of components when a sub-pixel PAM control circuit is integrated with a sub-pixel PWM control circuit. By using a shared PWM control circuit across multiple PAM control circuits, one can effectively conserve circuit layout space while simultaneously capitalizing on the advantages of the PWM circuit. This approach facilitates enhanced control over both the emission duration and current magnitude, which is significantly beneficial for operations at high-efficiency current points in uLED applications.

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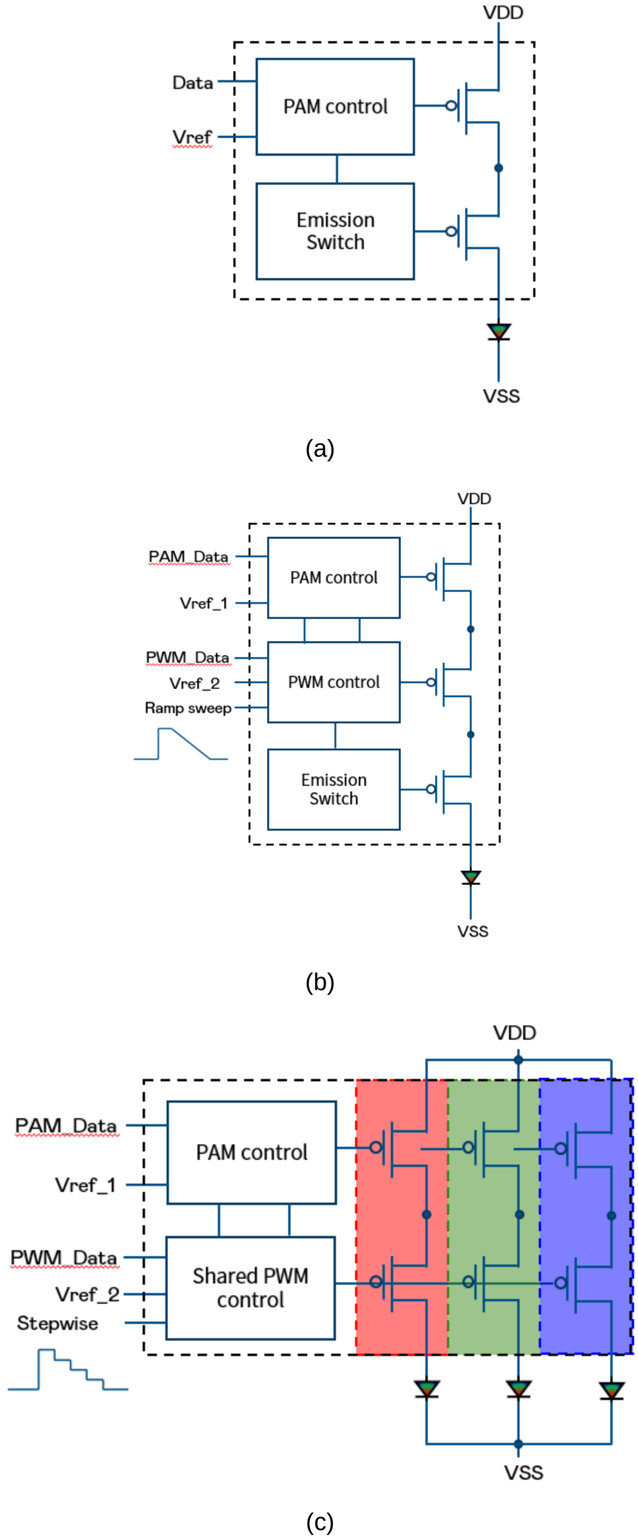

Figure 1. (a) PAM, (b) PWM, and (c) HPS circuit.

III. Panel specifications and quality

This section combines the findings regarding the spatial conditions and performance characteristics of three uLED driving circuits: PAM, HPS, and PWM. The organized PPI distributions for these circuits are illustrated in Table 1, where PAM circuits achieve a PPI up to 326, HPS circuits up to 225, and PWM circuits up to 100.

	PAM	HPS	PWM
PPI	PPI ≤ 326	PPI ≤ 225	PPI ≤ 100

Table 1. PPI diagram of PAM, PWM, and HPS circuits.

Power consumption varies across these circuits, particularly when red uLEDs operate within the medium to low current density range [4]. Figure 2 further indicates that PAM exhibits the highest power consumption at mid-low gray scales, while HPS shows intermediate consumption levels, and PWM circuits maintain the lowest consumption overall.

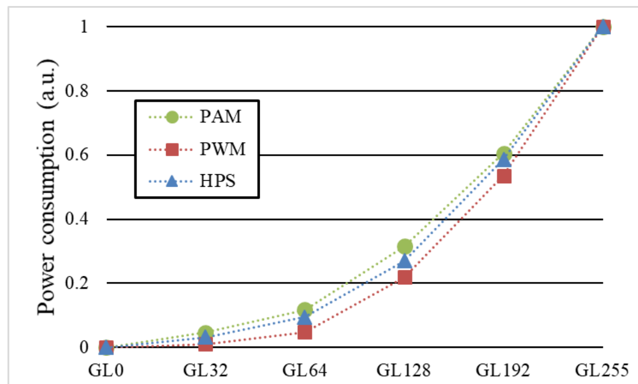

Figure 2. Comparison of power consumption

A specific comparison between HPS and PWM at low gray scales reveals that HPS outperforms PWM in managing current variation error rates caused by fluctuations in driving transistor threshold voltage (Vth) due to process uniformity or long-term operation. This performance advantage is detailed in Figure 3, which shows that PWM [5] struggles against Vth variations.

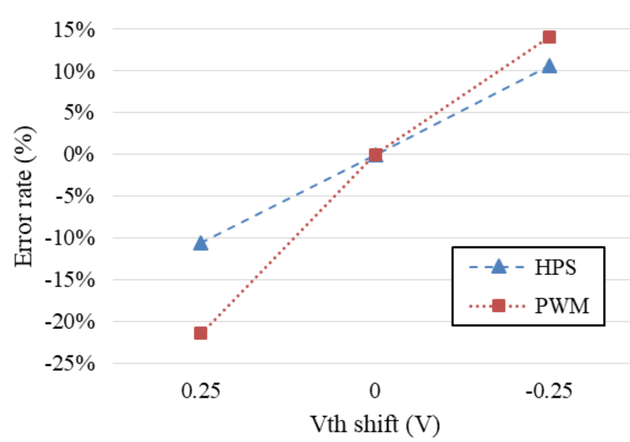

Figure 3. Comparison of driving current error rate at GL32

The falling time of driving current pulses in uLED displays significantly impacts various aspects of image quality, including color accuracy, brightness stability, motion blur, contrast, black state performance, and response time delays. Figure 4 presents the falling time (Tf) conditions for the three circuits, indicating that

HPS, advancing from a stepwise waveform [6], displays superior Tf performance compared to PWM [7].

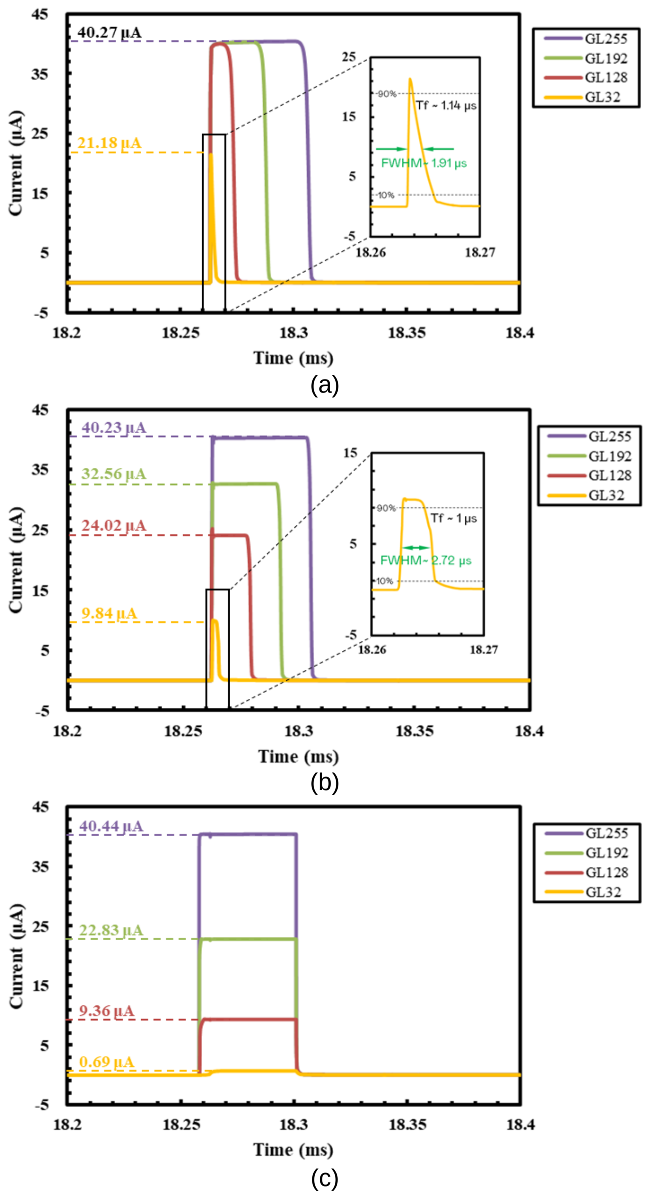

Figure 4. (a)PWM (b)HPS (c)PAM current pulse waveform

PAM pixel circuits offer distinct advantages for high-resolution displays, such as premium smartphones and professional monitors, achieving resolutions up to 326 PPI while effectively managing high gray levels, making them ideal for applications that demand exceptional visual fidelity. However, they have the highest elevated power consumption at mid to low gray levels.

Conversely, HPS circuits provide a balanced approach to performance and efficiency, making them suitable for mid-range devices like mainstream smartphones and general-purpose tablets, typically achieving resolutions up to 225 PPI. This hybrid design showcases relative stability against variations in Vth shifts while maintaining an efficient power profile. Nonetheless, their performance at higher gray levels may not rival that of dedicated PAM circuits.

PWM pixel circuits are primarily targeted toward low-end displays, such as budget smartphones and public displays, with resolution up to 100 PPI. Their lower pixel density limits their capability to meet high-resolution requirements. Furthermore, the potential for increased current error rates due to Vth shifts can adversely affect overall image quality.

In conclusion, the choice of pixel driving circuit drastically influences the specifications and quality of display panels. PAM circuits are optimal for high-end applications requiring high resolution and image clarity, while PWM circuits are better suited for low-end displays that prioritize cost efficiency. The HPS circuit emerges as a viable solution for mid-tier displays, underscoring the necessity of selecting an appropriate circuit design based on specific market segments and user requirements within the evolving landscape of display technology.

IV. Conclusion

Organic Light-Emitting Diodes (OLED) have attained significant maturity in terms of color accuracy and display performance, leading to their widespread adoption across various applications. In contrast, Micro Light-Emitting Diodes (µLED) are emerging as formidable contenders in the display technology landscape, characterized by exceptional brightness, durability, and superior display potential. This article provides a thorough examination of the advantages and challenges associated with these display technologies, emphasizing the potential of µLED to become a mainstream solution in future markets.

A comparative analysis of the operational mechanisms of OLED and µLED at equivalent brightness levels reveals that OLED commonly utilizes hold time driving (PAM), while µLED is required to reduce the emission duty cycle for efficiency. This necessitates an increase in current density for µLEDs, transitioning from nanometers (nA) to microamperes (µA), thereby requiring current pulse driving with multi-impulse strategies to mitigate flicker phenomena.

Further analysis comparing PAM with the HPS circuit operation indicates that while PAM operates at lower current densities in the mid to low grayscale range, it demonstrates limitations in luminous efficiency. Conversely, hybrid driving elevates current densities in the low grayscale region, which is particularly beneficial for applications involving red color displays. This hybrid approach not only contributes to a reduction in power consumption but also addresses uniformity issues typically encountered with low grayscale outputs in the PWM systems. In PWM driving configuration, low grayscale currents yield triangular waveform characteristics, resulting in current error rates influenced by Vth variations exceeding 20%. The incorporation of PWM, utilizing either ramp or stepwise waveforms, substantially enhances the consistency of current and brightness.

Moreover, hybrid operations are found to be more applicable for high PPI scenarios compared to PWM driving. The selection of appropriate µLED pixel circuit configurations utilizing PAM, PWM, or HPS methods should be guided by the specific panel specifications and application requirements.

In conclusion, while OLED technology continues to dominate the display market due to its established performance, µLED presents a compelling alternative with distinct advantages positioning it as a promising candidate for future display innovations. The optimal integration of diverse driving techniques and circuit designs will be crucial for maximizing the potential of these evolving technologies.

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