# The Latest Trends on CMOS Backplane for µLEDoS Microdisplay for AR Smart Glasses

***Myunghee Lee, Jonggu Jeon, Jihaeng Lee and Jinwoong Jang***
**Sapien Semiconductors Inc., Pangyo, Korea**

## Abstract

***This paper explores emerging trends in the implementation of CMOS (Complementary Metal-Oxide-Semiconductor) backplane for µLEDoS (Micro-LED on Silicon) microdisplays in future AR smart glasses. The design and performance of these backplanes are influenced by key factors such as Field of View (FOV), latency, motion blur compensation, form factor, power consumption, and manufacturability. An expanded FOV, which is crucial for an immersive user experience, necessitates higher display resolution, impacting power efficiency, die size, and overall system performance. Additionally, future AR smart glasses require advanced motion compensation techniques to mitigate image artifacts caused by head or eye movement. This paper introduces the design concept and operational principles of the Memory-Inside-Pixel (MIP) pixel architecture, with a particular focus on pixel-level image operations aimed at minimizing motion blur and enhancing visual quality.***

## Author Keywords

µLEDoS, CMOS backplane, microdisplay, motion blur, FOV, PWD, MIP (Memory-Inside-Pixel)

## 1. Introduction

Recently, there has been a noticeable increase in the availability of consumer-grade AR (Augmented Reality) smart glasses incorporating µLEDoS microdisplays [1]. However, most AR smart glasses in the market still rely on traditional display architectures that primarily support four key requirements: resolution, frame rate, dynamic range, and color gamut. The majority of microdisplay modules currently available feature VGA-resolution, monochrome-based color modes, 8-bit or lower dynamic range, and a limited color gamut [2–4].

For a spatial computing device, the microdisplay used in AR wearable devices must meet additional requirements beyond those of traditional microdisplays [5]. As described in Table 1, these include a wide field of view (FOV), accommodation-vergence support, low latency, stereo vision, and a high degree of freedom. Such advanced microdisplays are referred to as Perceptual Wearable Displays (PWD) to distinguish them from conventional display technologies [6]. A PWD must provide an immersive user experience while minimizing motion blur during head and/or eye movements, a feature known as world-locking [7].

A typical Perceptual Wearable Display (PWD) is expected to feature four times the resolution of 640 x 480 (VGA), a pixel density of 10,000 PPI (Pixels Per Inch) or higher, a FOV of at least 60 degrees, and a frame rate of 180 Hz or higher, all within a compact display size of 0.2 inches or smaller. Achieving these specifications requires a pixel pitch of 2.5 µm or less.

The requirements for a PWD must be met while ensuring lower power dissipation of the backplane and a compact form factor. These constraints, in turn, dictate the choice of the CMOS process node. Currently, 28nm and 22nm CMOS process nodes are popular choices for µLEDoS CMOS backplane design [8]. However, to achieve higher pixel density while minimizing power consumption, adopting a more advanced CMOS process, such as 16nm, may be considered. However, the increased fabrication costs associated with smaller process nodes would pose a significant burden on manufacturing feasibility and overall product cost.

**Table 1.** Conventional Display vs. PWD display

| Conventional (or 2D) | PWD (or 3D) |
|---|---|
| Resolution,<br>Frame rate,<br>Color Depth, &<br>Color Gamut | Resolution, Frame rate,<br>Color Depth, Color Gamut<br>**Field of View (FoV),**<br>**Stereo,**<br>**Latency,**<br>**Accommodation-Vergence, &**<br>**Degree of Freedom** |

Another significant challenge lies in the micro-LED device itself. Currently, monochrome panels are favored over full-color monolithic panels due to manufacturability constraints and cumulative yield considerations [2]. While a VGA resolution remains the mainstream in mass production, higher resolutions, such as 2×VGA and 4×VGA, are expected to be introduced soon. Achieving such high resolutions presents a major challenge in terms of non-uniformity within the active array. To address this issue, a tailored de-mura scheme is required to effectively compensate for pixel non-uniformity in micro-LED displays.

Unlike traditional displays, where the user's head and eyes remain relatively stationary, AR smart glasses with a PWD require motion-compensated pixel operations to maintain visual clarity. Without a proper scheme, motion blur occurs, degrading the user experience. This paper proposes a solution to address this challenge.

## 2. Monochrome vs. Polychrome backplane

In consumer-grade AR smart glasses, two types of µLEDoS microdisplays are used: monochrome and polychrome. Notably, polychrome displays achieve full color by combining three RGB (Red, Green, & Blue) monochrome display panels as shown in Fig. 1. A single full-color display panel for AR glasses is not yet ready for mass production although significant efforts are underway in the industry.

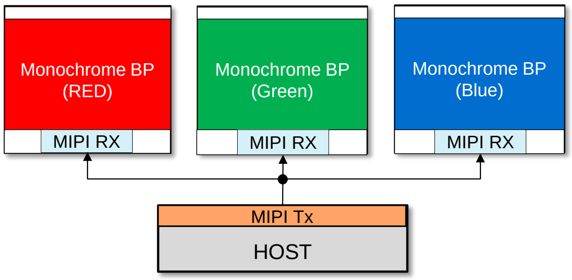

**Figure 1.** High-speed interface configuration with 3 monochrome panels.

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For monochrome displays, a pixel pitch of 2.5 µm is expected to be introduced this year, although displays with a 4 µm pixel pitch are currently adopted in mass production [4]. In the near future, a further reduction to a 2 µm pixel pitch is anticipated. For single RGB panels, CMOS backplanes with a 5 µm pixel pitch are already available [8], with 4 µm pixel pitch projected as the next advancement. Achieving a smaller pixel pitch at the backplane requires the adoption of a finer CMOS process node, such as 16nm or smaller, especially for MIP pixel architecture. However, this introduces significant challenges, including increased fabrication costs, performance constraints of µLEDs, and the complexity of hybrid-bonding solutions. Therefore, innovative approaches are necessary to strike a balance between reducing pixel pitch and maintaining cost efficiency.

A polychrome display utilizing three separate panels introduces several design challenges at the CMOS backplane level. One of the primary challenges is the high-speed interface scheme between the host processor and the three individual backplanes, as illustrated in Fig. 1. A single host processor must manage the RGB data for all three panels simultaneously. As display resolution increases, the required data throughput at the interface grows significantly. Unlike a simple point-to-point interface, a multi-drop interface scheme woud be necessary to accommodate this configuration efficiently.

Another challenge is the synchronization of the three backplanes during illumination. To maintain consistent color quality, the individual RGB display panels must be precisely synchronized during the illumination time.

## 3. Pixel Shift Operation for Motion Blur

One of the primary challenges associated with a PWD is mitigating motion blur caused by head and/or eye movements, a process commonly referred to as "motion compensation." Unlike traditional stationary displays, where the user's gaze remains fixed relative to the screen, PWD must incorporate motion-compensated pixel operations to minimize motion blur and maintain visual clarity. Effective motion compensation relies on an optimized rendering pipeline capable of dynamically adjusting pixel positions to achieve world-locked rendering [6].

To prevent motion blur in µLED AR smart glasses, the maximum illumination time must be carefully controlled based on the frame rate and the desired persistence of each frame. Motion blur occurs when pixels remain illuminated for an extended duration while the image updates, resulting in a smear effect as the eye tracks motion.

The maximum illumination time or duty time defines how long a pixel is allowed to emit light per frame. It means that,

$$\mathit{Maximum\ Illumination\ Time} = \frac{1}{\mathit{Frame\ Rate}} \qquad (1)$$

For a display with a 40° horizontal FOV and a resolution of 1,280 pixels along the horizontal axis, a head rotation of 60° per second results in an angular displacement of approximately 0.06° per millisecond. Given that each pixel corresponds to 0.031° of the visual field, this movement translates to approximately 2 pixels per millisecond. With a typical display duty time of 11 milliseconds (or 90Hz frame rate) in a typical AR application, each pixel undergoes a displacement of approximately 22 pixels, leading to significant motion blur:

$$2\ [\mathit{pixels}/\mathrm{msec}]\ \mathrm{x}\ 11\ [\mathrm{msec}] = 22\ \mathrm{pixels} \qquad (2)$$

Even for displays with a wider FOV (e.g., 60°) and higher resolution (e.g., greater than 1,280 pixels), the approximation of 2 pixels/msec remains reasonably accurate, with only a small margin of error.

To maintain acceptable image quality, a pixel illumination time of 1 millisecond or less is generally recommended [6], as it helps reduce motion blur, particularly when users hold their heads more steadily—a common scenario in AR applications. Head motion can vary significantly, typically ranging from 5° to 100° per second. In seated conditions, head motion is approximately 30° per second, whereas head movement during walking or other dynamic activities can exceed 70° per second.

To mitigate motion blur, a technique known as the "pixel shift" operation is proposed, as illustrated in Fig. 3 and Fig. 4. This method involves shifting the pixel image up to 15 times between frames. Utilizing motion tracking data, the image can be adjusted in four directions—left, right, up, and down—based on the direction of the user's head movement. By rapidly repositioning the pixel image to an adjacent pixel, this operation compensates for both head and eye movements, effectively reducing motion blur and enhancing visual stability.

To enable the pixel data shift operation between adjacent pixels, each pixel circuitry incorporates a Memory-Inside-Pixel (MIP) structure that supports a dynamic range, along with associated multiplexer circuitry and timing control. This configuration allows the pixel image data to be dynamically shifted in the corresponding direction based on the user's head movement, ensuring accurate motion compensation and reduced motion blur.

Integrating all necessary components within a very small pixel area such as 2.5µm x 2.5µm presents a significant challenge, as it

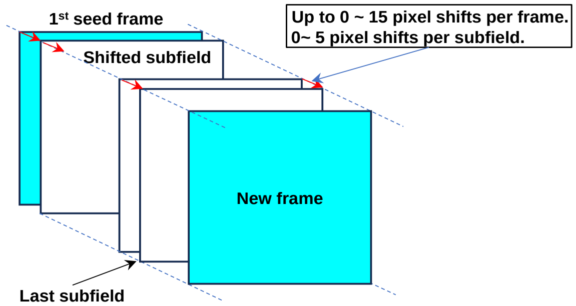

**Figure 3.** Pixel shift operation between the frame.

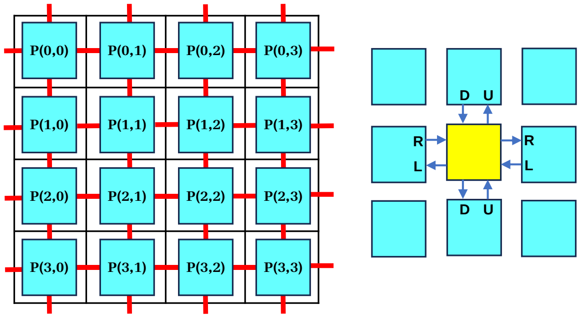

**Figure 4.** Block diagram of the pixel shift operation.

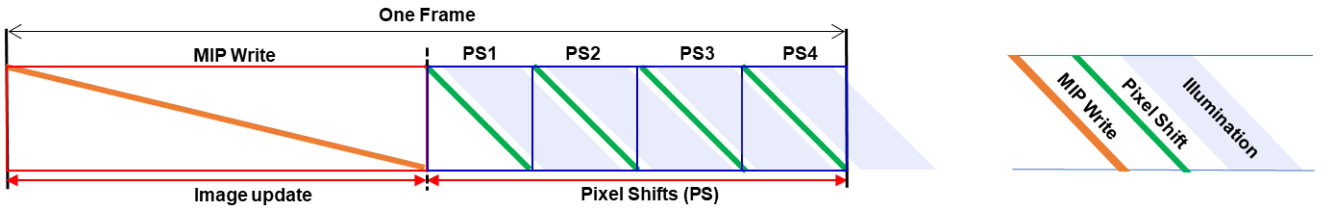

**Figure 5.** Timing diagram of the pixel shift operation.

requires optimizing the design of memory-in-pixel structures, multiplexers, and timing control circuitry while maintaining high display performance and efficiency.

Fig. 5 illustrates the timing diagram of the pixel shift operation, which allows for a maximum of four consecutive sub-frames. Within each frame time, three operations are executed: MIP Write, Pixel Shift (PS), and Illumination. The pixel shift in each sub-frame allows for up to four shifts before illumination, resulting in a total of 16 shifts per frame. In case of 11ms frame time (or 90Hz frame rate), MIP Write would take a half of the frame time which is around 5.5ms. The rest 5.5ms is assigned to pixel shift/illumination period. If there are 4 sub-fields (PS), each sub-field would have 1.375msec, during which the pixel shift operation and illumination would occur.

The illumination time of each sub-field (PS1 to PS4) can also be adjusted based upon the available time budget. Considering the shift rate of 2 pixels per millisecond based on eariler scenario, performing four sub-fields between the frame is considered reasonable, as it strikes a balance between effective motion compensation and maintaining an adequate timing margin for both the pixel shift and illumination within the pixel architecture. During each sub-field operation (PS1 ~ PS4), the number of the data shifting of each sub-field (green color line at Fig. 5) can allow up to 4 consecutive shifts.

For an immersive AR display, a persistence of around 1 millisecond is considered optimal to eliminate motion blur during head tracking. Thanks to its nanosecond-level response time, an µLED device can achieve such a short illumination window without any ghosting or lag, ensuring smooth and clear visual experiences. Unlike other display solutions, µLED can maintain high brightness even with minimal illumination time, which is crucial for AR display that operate in varying ambient light conditions.

Another design approach to minimize the motion blur would be to update the image data at a faster frame rate, exceeding 240 to 360 Hz, which could yield similar visual quality. However, this method requires higher data throughput between the host and the display panel, and this demand increases with a larger FOV or higher resolution. Additionally, a higher frame rate leads to greater power dissipation across the overall system. Therefore, careful design trade-offs must be considered when selecting the appropriate architecture.

## 4. Summary

A Perceptual Wearable Display (PWD) is a device designed to seamlessly integrate digital information with the user's natural perception of the world. This paper examines key design parameters of a CMO backplane of PWDs, with a particular focus on µLED-based displays for AR smart glasses. One of the most critical challenges in this field is mitigating motion blur during head movement. A promising solution is Pixel Shifting, a technique that leverages the CMOS backplane's inherent capability to execute this function with minimal processing demand on the host system. This feature is crucial for achieving world-locking and ensuring a stable, clear visual experience. This capability is essential for achieving world-locking and minimizing motion blur. Additionally, with its nanosecond-level response time, µLED technology is the most suitable display solution for such applications. Given its pivotal role in enhancing visual stability, motion compensation is expected to become an essential feature for microdisplays used in AR smart glasses and spatial computing devices.

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