Improvement of the low gray-level expression using hybrid pulse width modulation and pulse amplitude modulation driving method for a micro light-emitting diode pixel circuit

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ABSTRACT
A novel hybrid pulse width modulation (PWM) and pulse amplitude modulation (PAM) (HPP) driving method is proposed for improving the low gray-level expression of a micro light-emitting diode (µLED) display. At the high and middle gray-levels, PWM is adopted in order to suppress the wavelength shift of µLEDs. At the low gray-level, PAM is applied when the emission time and current of µLEDs simultaneously decrease. The HPP driving method is simulated by using a simplified p-type low-temperature polycrystalline silicon (LTPS) thin-film transistor (TFT)-based µLED pixel circuit. HPP driving exhibits stable PWM and PAM operations. Furthermore, HPP driving guarantees a data voltage range approximately 14 times larger than PWM driving, thus resulting in a robust operation with a maximum error rate of 3.83% under data signal distortion. Consequently, the µLED pixel circuit adopting HPP driving improves the low gray-level expression and demonstrates a robust circuit operation.

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1. Introduction
Micro light-emitting diodes (µLEDs) have caused significant interest as next-generation display devices due to their numerous advantages, such as high contrast ratio, high reliability, high luminance, and fast response time without burn-in issues [1–4]. The majority of µLED displays have used printed circuit boards (PCBs) and silicon chip-based backplanes. Recently, µLED displays based on a thin-film transistor (TFT)-based backplane have been researched due to their low cost and high productivity [5–7]. Furthermore, TFT-based pixel circuits and driving methods for µLED displays have been investigated in order to improve display performance [8,9]. Conventional organic light-emitting diode (OLED) pixel circuits adopt pulse amplitude modulation (PAM), wherein the gray-level is expressed according to the OLED driving current level. However, it is difficult to use conventional PAM in µLED displays due to the wavelength shift according to the µLED driving current density [10]. Therefore, µLED displays require a pixel-driving circuit that uses pulse width modulation (PWM) driving for gray-level expression [11].

Although PWM has a high grayscale expression capability without wavelength shift, TFT-based pixel circuits using PWM have an issue at a low gray-level. Ideally, for PWM driving, the emission time gradually changes with a constant driving current across the entire grayscale range, and the µLED driving current sharply decreases at the end of the emission. In practice, however, the µLED driving current decreases at a low gray-level and cannot be sharply reduced due to the current driving capability and switching time of TFTs. As the emission time and µLED driving current simultaneously decrease at a low gray-level, the luminance dramatically changes, thus resulting in a narrow data voltage range and image distortion due to data signal variations. This phenomenon is attributed to the current-driving capability and switching time of TFTs. As a result, increasing the size of TFTs or using the switching circuit units to improve current-driving capabilities could be a potential solution to the aforementioned issues. However, these methods increase the complexity of the pixel circuit and limit the application of µLED devices. Therefore, it is necessary to investigate alternative driving methods in order to overcome these challenges.

In this study, a novel hybrid PWM and PAM (HPP) driving method is proposed to improve the image quality of µLED displays at a low gray-level. The HPP driving...
method uses PWM at high and middle gray-levels and PAM at a low gray-level. The HPP operation is investigated by using circuit simulation. The simulation results confirm that the HPP driving method exhibits high grayscale expression capability. Furthermore, the HPP driving method shows a larger data voltage range and a lower luminance error rate compared to PWM.

2. Development of novel HPP driving method

Figure 1 shows the µLED current waveforms with various gray-levels based on PWM. With a constant LED current, the emission time decreased as the gray-level decreased. However, the µLED current decreased as the emission time decreased at a low gray-level. The emission time when the µLED current started to change was defined as the peak gray-level threshold time (t\text{PEAK}). When the emission time was lower than t\text{PEAK}, the emission time and µLED current simultaneously decreased, thus resulting in a dramatic change in the grayscale. Image distortion occurred as a result of data signal variations caused by circuit component fluctuations and data signal line load.

Figure 2 illustrates a conceptual diagram of the proposed HPP and conventional PWM driving operations. The graph axes represent the µLED current, emission time, and gray-level. First, the conventional PWM driving modulated the gray-levels as the emission time changed, and maintained a constant current by applying constant PAM data (V\text{DATA}_PAM). In practice, as previously mentioned, the current decreased along with the emission time below a certain gray-level with t\text{PEAK}. Furthermore, the amount of charge, which is the integral of the µLED current over the emission time, rapidly reduced. The range of PWM data (V\text{DATA}_PWM) voltage for expressing the low grayscale was significantly reduced as the amount of charge had a proportional relationship with the luminance and gray-level. In order to express the low gray-level appropriately, a sufficient margin of the V\text{DATA}_PWM range must be guaranteed.

A novel HPP driving method was developed in order to solve this issue. The proposed HPP driving method used both PWM and PAM driving methods to express the grayscale. Conventional PWM driving was used at high and middle gray-levels, with an emission time longer than t\text{PEAK}. However, PAM driving was used in the low gray-levels, with an emission time shorter than t\text{PEAK}. The emission time was fixed to t\text{PEAK} by constant V\text{DATA}_PWM, and the V\text{DATA}_PAM was changed to express the grayscale. Only the current varied with the emission time of t\text{PEAK}; therefore, the HPP was able to prevent the abrupt charge reduction that occurs in conventional PWM driving. Consequently, the proposed HPP driving has a wide range of V\text{DATA}_PAM, thereby improving the stability of the gray-level expression.

Although HPP driving can improve the low gray-level expression capability, the wavelength shift of the µLED may occur due to µLED current changes at a low gray-level. However, based on the human visual perception (HVS) model, sensitivity to luminance changes is greater in the middle and high gray-levels than in the low gray-levels [12]. Therefore, when expressing low gray-levels below t\text{PEAK} in the µLED pixel circuit, even if the peak current decreases, it is perceived less than in high and middle gray-levels. Consequently, a novel HPP driving method was proposed for the stable low gray-level
expression of μLED displays. However, the driver circuit is complicated since PWM and PAM should be randomly used for gray-level expression. In addition, the gray-level of $t_{PEAK}$ can differ for each panel, and the driving algorithm process to find $t_{PEAK}$ can be complicated. These issues can be resolved if the process deviation for each panel or algorithm development for the driver circuit is improved.

3. Operation of novel HPP driving method

A simplified μLED pixel circuit was designed to investigate the proposed HPP driving method. Figure 3 illustrates the circuit schematic and timing diagram of the μLED pixel circuit for HPP driving with p-type low-temperature polycrystalline silicon (LTPS) TFTs. Since LTPS TFTs exhibit high mobility and stability, they are suitable as backplanes for high-brightness μLED displays [13–17]. The simplified pixel circuit consisted of five TFTs and two capacitors. T1 was a PWM switching TFT, controlled by a PWM scan signal (SPWM[n]) for applying $V_{DATA\_PWM}$. T2 was a PAM switching TFT, controlled by a PAM scan signal (SPAM[n]) for applying $V_{DATA\_PAM}$. T3 and T5 were the PWM and PAM driving TFTs, respectively. T4 was an emission TFT, controlled by an emission control (EMI) signal. $V_{DATA\_PWM}$ and $V_{DATA\_PAM}$ were stored in C1 and C2, respectively. The operation of the proposed circuit was divided into three periods, as shown in Figure 3(b).

3.1. PWM data input

At the beginning of each frame, $V_{DATA\_PWM}$ was written progressively for all gate lines. T1 was turned on by SPWM[n], and $V_{DATA\_PWM}$ was stored in C1 because the sweep control (SWEEP) signal was a constant voltage. As shown in Figure 3(c), $V_{DATA\_PWM}$ was a variable that controlled the emission time when the emission time was greater than $t_{PEAK}$. In contrast, $V_{DATA\_PWM}$ had a constant value below $t_{PEAK}$, and the emission time was fixed to $t_{PEAK}$, as shown in Figure 3(d).

3.2. PAM data input

During this period, $V_{DATA\_PAM}$ was written progressively for all gate lines, immediately after writing $V_{DATA\_PWM}$. T2 was turned on by SPAM[n], and $V_{DATA\_PWM}$ was stored in C2. As the HPP operated the PWM driving when the emission time was larger than $t_{PEAK}$, $V_{DATA\_PAM}$ was a constant value, as shown in Figure 3(c). However, $V_{DATA\_PAM}$ changed according to the grayscale when the emission time was shorter than $t_{PEAK}$, and the HPP operated the PAM driving.

3.3. μLED emission

Finally, all of the μLEDs emitted light simultaneously. The EMI signal had a low-level voltage, and the SWEEP signal voltage waveform gradually changed at the same
Figure 3. (a) Circuit schematic, (b) timing diagram, (c) PWM driving with constant PAM data, and (d) PAM driving with constant PWM data of the simulated HPP driving µLED pixel circuit.

4. Results and discussion

The proposed HPP driving operation was investigated by using a circuit simulation (SmartSpice, Silvaco). In order to confirm the improvement of the gray-level expression of the µLED pixel circuit, the conventional PWM and proposed HPP driving were simulated under the same conditions with an 8-bit grayscale expression and a single frame time of 16.6 ms. Since the µLED emission period was set to 4 ms, the emission duty ratio was 48%, and the peak µLED current was set to 50 μA. The current waveforms were listed from 255G to 1G in order to confirm that the gray-level was expressed without abnormality. Figure 4(a) presents the simulated current waveform of the overall gray-level expression by using conventional PWM driving for the µLED pixel circuit. As previously mentioned, $t_{PEAK}$ was observed in conventional PWM driving, as shown in Figure 4(a). In the case of the proposed µLED pixel circuit, 80G can be expressed at $t_{PEAK}$. At the gray-level below 80G, the peak current was not a constant value and it decreased with the emission time. Figure 4(b) shows the current waveform from 80G to 1G by using conventional PWM driving. The target current level of 50 μA could not be maintained, and both the current and emission times decreased to express a gray-level of 80G or less. The lower the gray-level, the lower the PWM data stored in the T3 gate node (node A). Thus, the driving capability of T3 increased because the gate–source voltage of T3 ($V_{GS,T3}$) steadily decreased. The values of $V_{GS,T3}$ decreased from 80G to 1G during the rise time of 100 ns. Consequently, when the gray-level decreases, the charged voltage of the T5 gate node (node B) increases during a rise time of 100 ns. Accordingly, when the µLED emits, the maximum current is different in the low gray-level expression of 80G or less. Figure 4(c) shows the current waveform for the full gray-level expression of the proposed HPP driving. In the gray-level range from 80G to 255G, the proposed HPP driving operation performance was equivalent to conventional PWM driving. When expressing a gray-level of 80G or less, the emission time was maintained at $t_{PEAK}$ by fixing $V_{DATA,PWM}$. For a gray-level below...
Figure 4. Simulated current waveforms: (a) overall gray-level expression using conventional PWM driving, (b) low gray-level expression using conventional PWM driving, (c) overall gray-level expression using proposed HPP driving, and (d) low gray-level expression using proposed HPP driving.

80G, $V_{DATA\_PAM}$, which has a charge capable of expressing the same gray-levels, was applied for comparison with the conventional PWM driving. Figure 4(d) shows PAM driving at a gray-level of 80G or less with the same emission time. In contrast to conventional PWM driving, only the current flowing through the μLED was a variable in the gray-level expression.

Figure 5 shows a comparison of gray-level expressions between the conventional PWM and the proposed HPP driving. For PWM driving, the gray-level was expressed only according to changes in $V_{DATA\_PWM}$ ($\Delta V_{DATA\_PWM}$). For HPP driving, the grayscale was expressed according to changes in both $V_{DATA\_PWM}$ and $V_{DATA\_PAM}$ ($\Delta V_{DATA\_PWM} + \Delta V_{DATA\_PAM}$). The gray-level was expressed according to the sum of the data voltages ($\Delta V_{DATA\_PWM} + \Delta V_{DATA\_PAM}$), as shown in Figure 5(a). From 255G to 80G, both PWM and HPP driving had the same driving method and gray-level expression. Accordingly, $\Delta V_{DATA\_PWM}$ had 6.1 V and expressed 176 gray-levels from the maximum gray-level. In conventional PWM driving, when the gray-level was 80G or less, both the current and the emission time decreased. The amount of charge during μLED emission was dramatically reduced when the $V_{DATA\_PWM}$ changed, thus resulting in a significantly decreased gray-level. Therefore, gray-levels below 80G were represented within the $\Delta V_{DATA\_PWM}$ range of only 0.4 V. However, HPP driving had a $\Delta V_{DATA\_PWM} + \Delta V_{DATA\_PAM}$ of 5.3 V for gray-level expressions from 80G to 1G because the HPP driving operated PAM by fixing the emission time to $t_{PEAK}$ when the gray-level was 80G or less. Therefore, HPP driving had a data voltage range approximately 14 times larger than PWM for expressing low gray-levels. Figure 5(b) shows the gray-level expression abilities of PWM and HPP driving. In PWM driving, a sharp decrease of about 20G occurred according to a data voltage change of 0.1 V, whereas in HPP driving, a decrease of approximately 1G occurred.

Data signal distortion was caused by data line load and circuit component fluctuations depending on the pixel position in the display panel. When the source integrated circuit (IC) that generated the data voltage was present at the top of the panel, the data voltages that were transferred to the top and bottom of the panel were different. The luminance error rate was investigated depending on the data signal variations due to the data line load. A data line load consisting of a 4.4 kΩ resistor and a 19.4 pF capacitor was connected to both the $V_{DATA\_PWM}$ and $V_{DATA\_PAM}$ lines in order to simulate worst-case conditions for the display panel. Luminance was calculated by integrating the μLED current over the emission time.

Figure 6 depicts the luminance error rate of PWM and HPP driving as the gray-level varied. As the operation
Figure 5. Simulated low gray-level expression of µLED pixel circuit using HPP driving: (a) overall gray-level expression, and (b) low gray-level expression.

Figure 6. Simulated charge error rate of varying gray-levels.

5. Conclusion

A novel HPP driving method was proposed, and its operation and low gray-level expression capability were investigated by using a circuit simulation, with a simplified µLED pixel circuit based on a p-type LTPS TFT. The simulated results indicate that HPP driving exhibited a larger data voltage range compared to PWM driving, and a reliable expression of low gray-levels with a sufficiently small luminance error rate of less than 3.83% under data signal distortions due to the data line load. Consequently, the HPP driving method exhibited a robust operation and improved the expression of low gray-levels.

Disclosure statement

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**References**

[1] A. Laaperi, J. Soc. Inf. Disp 16, 1125 (2008).

[2] F. Templier, L. Benaisia, B. Aventurier, C. Di Nardo, M. Charles, A. Daami, F. Henry, and L. Dupré, Dig. Tech. Pap. - SID Int. Symp 48, 268 (2017).

[3] C.-C. Lin, Y.-H. Fang, M.-J. Kao, P.-K. Huang, F.-P. Chang, L.-C. Yang, and C.-I. Wu, SID Symp. Dig. Tech. Pap 49, 782 (2018).

[4] H.-M. Kim, J.G. Um, S. Lee, D.Y. Jeong, Y. Jung, S.H. Lee, T. Jeong, J. Joo, J. Hur, J.H. Choi, J.S. Kwak, and J. Jang, SID Symp. Dig. Tech. Pap 49, 880 (2018).

[5] H.A. Ahn, S.K. Hong, and O.K. Kwon, IEEE Trans. Circuits Syst. II Express Briefs 65, 724 (2018).

[6] T. Wu, C.W. Sher, Y. Lin, C.F. Lee, S. Liang, Y. Lu, S.W.H. Chen, W. Guo, H.C. Kuo, and Z. Chen, Appl. Sci 8, 1557 (2018).

[7] J.H. Kim, S. Shin, K. Kang, C. Jung, Y. Jung, T. Shigeta, S.Y. Park, H.S. Lee, J. Min, J. Oh, and Y.S. Kim, SID Symp. Dig. Tech. Pap 50, 192 (2019).

[8] T. Goto, K. Saito, F. Imaizumi, M. Hatanaka, M. Takimoto, M. Mizumura, J. Gotoh, H. Ikenoue, and S. Sugawa, IEEE Trans. Electron Devices 65 (8), 3250 (2018).

[9] Z. Gong, S. Jin, Y. Chen, J. McKendry, D. Massoubre, I.M. Watson, E. Gu, and M.D. Dawson, J. Appl. Phys 107, 013103 (2010).

[10] J. Oh, J.H. Kim, J. Lee, E.K. Jung, D. Oh, J. Min, H. Im, and Y.S. Kim, IEEE Electron Device Lett 42, 1496 (2021).

[11] W.S. Shin, H.A. Ahn, J.S. Na, S.K. Hong, O.K. Kwon, J.H. Lee, J.G. Um, J. Jang, S.H. Kim, and J.S. Lee, IEEE Electron Device Lett 38, 760 (2017).

[12] L. Yu, H. Su, and C. Jung,, IEEE Access 6, 36132 (2018).

[13] C.L. Lin, P.C. Lai, I.W. Shih, C.C. Hung, P.C. Lai, T.Y. Lin, K.H. Liu, and T.H. Wang, IEEE J. Solid-State Circuits 54, 489 (2019).

[14] N. Sugiura, C.-T. Chuang, C.-T. Hsieh, C.-T. Wu, C.-Y. Tsai, C.-H. Lin, C.-C. Liu, C.-Y. Liu, C.-N. Yeh, C.-Y. Liu, and Y.-C. Lin, SID Symp. Dig. Tech. Pap 50, 450 (2019).

[15] C.-L. Lin, and Y.-C. Chen, IEEE Electron Device Lett 28, 129 (2007).

[16] V.W. Lee, N. Twu, and I. Kymissis, Inf. Disp. (1975) 32, 16 (2016).

[17] C.L. Lin, C.C. Hung, P.S. Chen, P.C. Lai, and M.H. Cheng, IEEE Trans. Electron Devices 61, 2454 (2014).