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MicroLED Display with LTPS Backplane using Novel Driving Circuit and Optical Outcoupling Structure

Kunio Imaizumi[1], Masaya Tamaki[1], Katsumi Aoki[1], Ryoichi Yokoyama[1], Hiroaki Ito[1], Sho Nakamitsu[1], Katsumi Yamanoguchi[1], Masahiko Nishide[1], Fanny Rahadian[1], Seiji Matsuda[1], Erwin Lang[2], Lutz Hoeppel[2]

kunio.imaizumi.fj@kyocera.jp
[1] Kyocera Corporation, Shiga, Japan
[2] OSRAM Opto Semiconductors GmbH, Regensburg, Germany
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ABSTRACT

A 3.9” microLED display prototype based on LTPS backplane has been developed utilizing a newly-designed current and PWM hybrid driving scheme to lower the color shift thus allowing for a higher frame rate. A novel approach for a reflector cavity process to improve the outcoupling efficiency is also proposed.

1. INTRODUCTION

MicroLED displays receive more and more attention as a next generation visualization technology for several applications. As they combine excellent visual performances with low power consumption they have the potential of being superior to current high-end displays in luminance, color gamut, and motion picture quality [1)].

Active matrix (AM) driving of LTPS backplane provides various excellent properties for realizing microLED displays as already demonstrated in several publications including own work [2-5)]. In general, the conventional current driving bears an intrinsic problem for display applications due to the noticeable shift in emission wavelength of LEDs with current density [6)]. In order to avoid this problem, a PWM pixel circuit for grayscale control using LTPS TFTs has been proposed in a previous work [4)]. But bare PWM driving results in quite short on-state times at lower grayscales setting the limit toward higher frame rates.

Potentially high luminance is one of the prominent features of microLED displays. The light extraction is determined by pixel design, microLED architecture and refractive indices of the surrounding materials. In particular, the light emission from the side walls of microLEDs has to be considered. According to previous work [7)], micro-lens arrays or micro-reflector arrays have been reported as measures to alter the direction of the emitted light. While various micro-lens arrays could not achieve sufficient optical properties, micro-reflector arrays were effectively able to redirect light that is emitted at large angles toward the forward direction. However, the proposed realization of a micro-reflector array by standard wafer processing technologies after bonding of microLED chips is inadequate in case of a LTPS backplane. The application of wafer-scale adopted chip transfer to a huge backplane is very difficult, while the usage of standard TFT processes to form cavities on cut-out individual display panels – addressable by the transfer process – is not compatible with standard TFT processing.

In this paper, we propose novel approaches: a current and PWM hybrid driving scheme and a reflector cavity design that can be applied to the microLED displays based on LTPS backplane. Based on these technologies, we demonstrate a prototype of a 3.9-inch 153-ppi full color active microLED display.

2. CURRENT AND PWM HYBRID DRIVING

Fig. 1 depicts a schematic diagram of our newly designed pixel circuit for current and PWM hybrid driving. The circuit basically consists of two parts: one covers predominantly lower while the other one works mainly at higher grayscale values. Each part can be selected by the signal designated as ENB, as shown in Fig. 1. For our prototype, each red, green, and blue sub-pixel is addressed in an 8 bit scheme using current and PWM hybrid driving. For lower grayscales, light is emitted from the microLEDs for a certain period of time during one frame (PWM dominated). The current amplitude per microLED chip is adjusted according to the desired grayscale. To avoid a too high shift of the emission wavelength, the minimum current amplitude is limited to a certain value, as the intrinsic wavelength shift of LEDs is in particular large at very low current densities. Toward higher grayscales light is emitted from the microLEDs for a longer period of time (almost DC operation) and the desired grayscale level is mainly adjusted by the current amplitude accordingly.

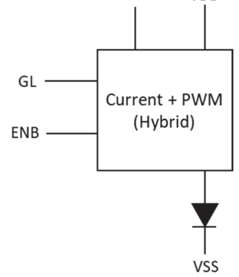

Fig. 1. Schematic diagram of our newly designed pixel circuit.

Fig. 2 depicts the measured relative luminance of the emitted light from green microLEDs as a function of the grayscale level by current and PWM driving. As shown, the luminance can be adjusted to fit to a gamma = 2.2 curve which proves that our newly designed current and PWM hybrid driving circuit works as required for state-of-the-art display applications.

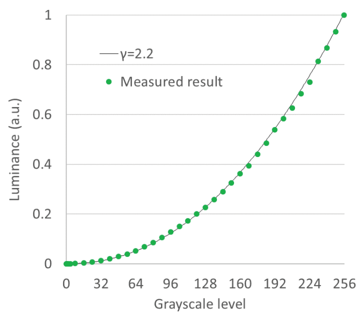

Fig. 2. Measured relative luminance of the emitted light from green microLEDs as a function of the grayscale level as derived by current and PWM hybrid driving.

In Fig. 3 a comparison between (a) current-only driving and (b) current and PWM hybrid driving is given. The length of each bar represents the +/-3σ deviation of the luminance across all green sub-pixels of our 3.9" prototype at lower grayscales. Defective sub-pixels were excluded from the evaluation. The variation can be considered as a superposition of the deviation of the characteristics of LTPS TFTs and microLED chips. With limiting the current density to a certain minimum value and accounting for that by combining current and PWM driving, the deviation of the luminance among sub-pixels can be significantly reduced.

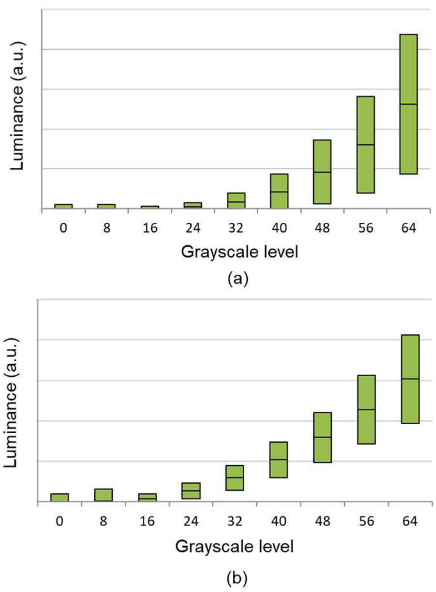

Fig. 3. +/-3σ variation of the luminance for (a) current-only driving and (b) current and PWM hybrid driving.

In Fig. 4 the above determined variations are translated into relative changes in CIE chromaticity evaluated for the grayscale range 40 to 256. Avoiding to drive microLEDs at a too low current amplitude allows to reduce the shift of the green emission color by 55% for CIEx and 65% for CIEy.

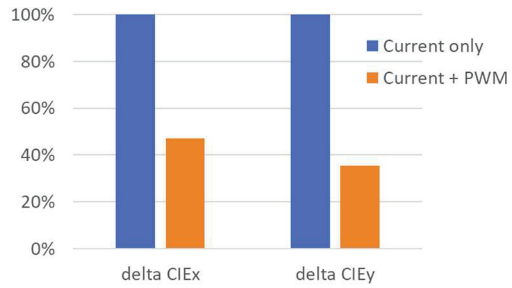

Fig. 4. Relative CIE chromaticity variation of green microLED emission for current-only driving vs. current and PWM hybrid driving.

3. EXTERNAL-OPTICAL COMPENSATION

The here presented new driving scheme can reduce the deviation of luminance and color shift. However, in comparison to state-of-the-art displays based on other technologies, the luminance deviation would still be large. A microLED display in particular suffers from the non-uniformity of the individual microLED chip characteristics as well as interconnect processes and the non-uniformity of the TFT backplane. Thus, an external-optical method is required to compensate for these influences. Such a method counteracts the non-uniformity by adding respective opposite gray-levels to the video signal [5]. For that we developed new driver ICs to operate hybrid driving and optimized the external-optical compensation method. Fig. 5 depicts the video data flow in case of applied external-optical compensation which includes luminance measurement for each pixel. Fig. 6 compares the luminance deviation without (blue) and with (red) external-optical compensation. The blue line corresponds to the data of Fig. 3 (b).

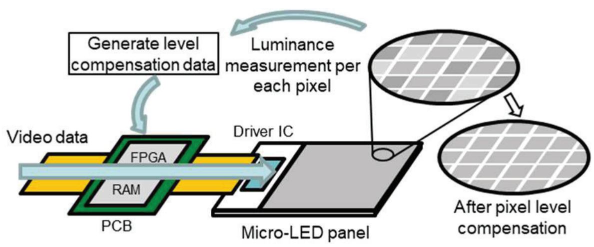

Fig. 5. Video data flow image through external-optical compensation.

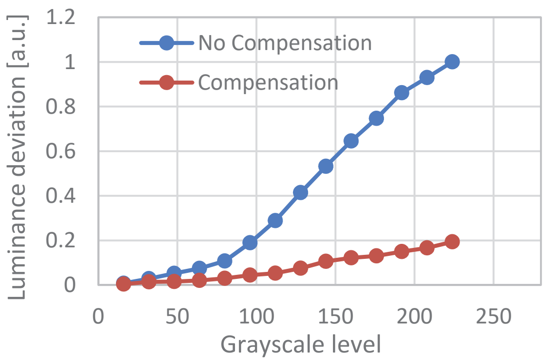

Fig. 6. Effectiveness of external-optical compensation.

4. REFLECTOR CAVITY

Fig. 7 illustrates a schematic cross sections of some light extraction architectures for a microLED display. As a premise, microLED chips are covered with insulator material such as resin or cover plate to protect them from corrosion or mechanical scratches. In the case without any outcoupling structure, as shown in Fig. 7 (a), total internal reflection occurs at the boundary between air and the insulator for light emitted at large angles. Reflector cavities can reduce the degree of total internal reflection and alter the direction of the light emission depending in particular on the cavity depth. If the reflecting cavity is shallow compared to the chip height still a large portion of the light emitted by the microLED chip undergoes total internal reflection as shown in Fig. 7 (b), By using a deeper reflector cavity, light emitted from the side surfaces can be redirected and leave the panel as shown in Fig. 7 (c).

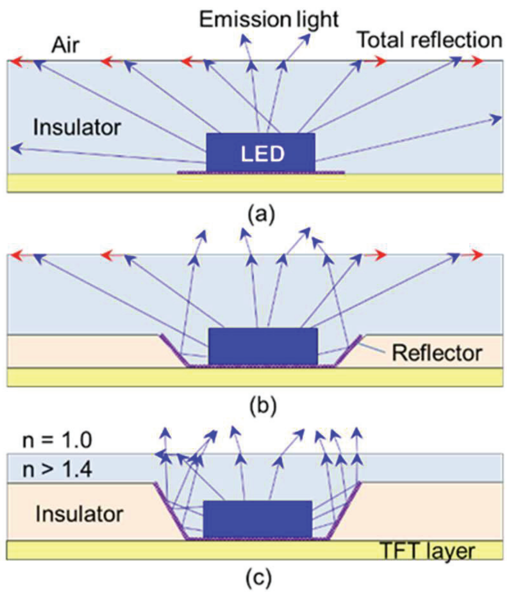

Fig. 7. Schematic cross sections of microLED structure with (a) no cavity, (b) shallow reflector cavity, and (c) deep reflector cavity.

In Fig. 8 the luminosity based on ray-tracing simulations (LightTools, Synopsys) is shown for various taper angles of the reflector cavity. The symbols designated as TA1 to TA5 correspond to reflector cavity tapers from small to large angles relative to a horizontal plane. The simulation results indicate that for each cavity depth there is a certain optimal taper angle. Since display processing favors not too deep cavities, we used taper angle TA2 for the prototype processing.

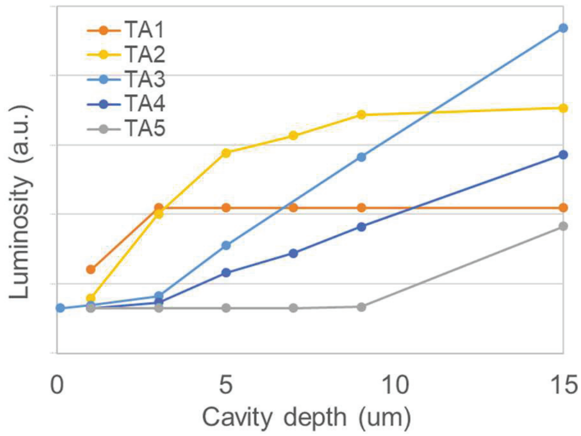

Fig. 8. Ray tracing simulation results as a function of the cavity depth and the taper angle.

5. 3.9” PROTOTYPE

As shown in Fig. 9, we have successfully developed a 3.9” full color microLED display prototype based on LTPS backplanes operated with current and PWM hybrid driving technology. Table 1 summarizes the specifications of the 3.9” microLED display prototype.

Fig. 9. Photograph of 3.9” microLED display prototype.

Table 1. Specification of 3.9" prototype.

Items	Specifications	Remarks
Backplane	LTPS	
Screen size	3.9-inch	
Resolution	480 x RGB x 360	
LED chip type	Red, Green, Blue	
Pixel size	166um	
PPI	153	
Gray scale	Current + PWM: 8bit	
Frame rate	240Hz	
Luminance	All white: 2000nits Peak white: 3000nits	White: D65
Contrast ratio	> 1,000,000:1	
Color gamut	83% (Rec.2020)	Area ratio
Viewing angle	> 178 deg.	

6. CONCLUSION

In this paper, the newly- designed current and PWM hybrid driving technology has been proposed to avoid the application of lower current densities to microLED chips, resulting in a reduction of the deviation of the luminance and the color shift at lower grayscale levels. Additionally, an optimized external-optical compensation provides further better luminance uniformity. Furthermore, a specific reflector cavity design that can be implemented with microLED displays based on LTPS backplane, has also been proposed to increase the luminance. Finally, we have successfully developed a 3.9" full color microLED display prototype based on LTPS backplane. The prototype showed excellent performances that proves the validity of the driving technology proposed in this paper.

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