Lifetime Extension Method for Active Matrix Organic Light-Emitting Diode Displays Using a Modified Stretched Exponential Decay Model

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***Abstract*— In this letter, we propose a compensation method for organic light-emitting diode (OLED) degradation occurring in a digital driving scheme for active-matrix OLED displays. The proposed method, in which we are the first to propose, employs the modified stretched exponential decay (SED) model to characterize the OLED degradation and compensates for the associated luminance decrease; the lifetime of an OLED panel can thereby be extended. The OLED panel is fabricated using low-temperature poly-Si thin-film transistors, and measured to verify the modified SED model and the proposed compensation method. The measurement results show that the luminance degradation with and without the proposed method is 0.3% and 6%, 4% and 17.8%, and 7.4% and 30.4%, for red, green, and blue OLEDs, respectively. This measurement is taken after 40 h of operation under a 350 cd/m^2 initial luminance. Accordingly, the proposed compensation method extends the lifetime of the OLED panel up to 72.5, 15.5, and 20.75 times longer in red, green, and blue OLEDs, respectively, compared with the conventional method.**

***Index Terms*— OLED degradation, digital driving, compensation, AMOLED, stretched exponential decay model, lifetime extension of AMOLED.**

I. INTRODUCTION

IN ACTIVE-MATRIX organic light-emitting diode (AMOLED) display, the analog driving that uses a current source in each pixel [1]–[3] has a problem involving variation in pixel luminance caused by a variation in the electrical characteristics of backplane thin film transistors (TFTs). To reduce the variation in pixel luminance, a compensation circuit is included in each pixel; however, this reduces the resolution and yield of AMOLED panels. Digital driving for AMOLED displays [4], [5] has been researched to enhance the immunity to the variation in the electrical characteristics of TFTs because it uses driving TFT as a switch rather than a current source. Thus, digital driving has several advantages such as high resolution and high image uniformity due to its simple structure and high immunity to the variation of TFT characteristics. However, digital driving has a critical problem; it has a shorter lifetime than analog driving due to organic light-emitting diode (OLED) degradation. In analog driving, as the internal resistance of the OLED increases due to degradation, the OLED luminance does not decrease because the current source supplies the emission current to the OLED regardless of the internal resistance. However, in digital driving, the increased internal resistance of the OLED increases the voltage drop across the resistance, and the effective anode-to-cathode voltage of the OLED decreases; the OLED luminance thereby decreases.

To solve the aforementioned problem in digital driving, the stretched exponential decay (SED) model [6] has been developed to characterize the OLED degradation. However, this model is only valid when the duty ratio of the emission is constant. In digital driving, the duty ratio of the emission should be increased to compensate for the OLED degradation because the OLED luminance is proportional to the duty ratio. However, as the duty ratio increases, the stress to the OLED increases, and thereby the OLED degradation is accelerated. Therefore, a new model for OLED degradation that accounts for the change in duty ratio is required.

In this letter, we propose a modified SED model for OLED degradation and a digital driving compensation method to extend the lifetime of an AMOLED panel. Previously reported external compensation methods [7]–[9] for OLED degradation using analog driving requires additional external sensing circuits and a large number of pixel components compared to the methods using digital driving. On the other hand, the proposed method, which uses pre-defined model and parameters for OLED degradation, improves the yield of the panel and reduces the system cost.

II. MODIFIED SED MODEL FOR OLED DEGRADATION

In the previously reported SED model of OLED degradation [6], the OLED luminance with respect to time, $L(t)$, is expressed as

$$L(t) = L_0 \exp\left[-\left(\frac{t}{\tau}\right)^{\beta}\right], \tag{1}$$

where L_0, τ, and β are the initial OLED luminance, the characteristic time scale of decay, and a stretching exponent,

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Manuscript received December 22, 2014; revised January 13, 2015 and January 15, 2015; accepted January 17, 2015. Date of publication January 21, 2015; date of current version February 20, 2015. The review of this letter was arranged by Editor B.-L. Lee.

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Digital Object Identifier 10.1109/LED.2015.2394451

respectively. From (1), the OLED luminance can be estimated using τ and β extracted from the measured L-t curve of the OLED panel. However, the estimated OLED luminance using (1) cannot represent the luminance change according to the duty ratio because the duty ratio is not taken into consideration in the previous SED model.

To reflect the duty ratio in the model, it is assumed that β is constant and τ is a function of the time-dependent duty ratio. The relationship between initial luminance and half lifetime of OLED can be represented as ${L_0}^n t_{1/2} = k$, where L_0, n, $t_{1/2}$, and k are initial luminance, acceleration coefficient, half lifetime of OLED, and a constant, respectively [6]. $t_{1/2}$ can be calculated from (1) by substituting $0.5L_0$ for $L(t)$, and $t_{1/2} = \tau(\ln 2)^{-\beta}$. Thus, ${L_0}^n \tau = k'$, where k' is a constant. Since the luminance of OLED is proportional to duty ratio (D), using the proportional relationship between L and D, and the inversely proportional relationship between ${L_0}^n$ and τ, $\tau(t)$ can be derived as

$$\tau(t) = \tau_0 \left(\frac{D_0}{D(t)}\right)^n, \tag{2}$$

where τ_0 and D_0 are the initial value of τ and D, respectively, at $t = 0$. To simplify the model, we assumed that $n = 1$, accordingly, $\tau(t) = \tau_0 D_0 / D(t)$. In addition, the relationship between the extracted and initial τ can be given by $\tau_0 = \tau_{meas} D_{const} / D_0$, where τ_{meas} and D_{const} are the extracted τ from the measured L-t curve of the OLED panel and the constant duty ratio during the measurement, respectively. By substituting τ_0, $\tau(t)$ can be expressed as $\tau(t) = \tau_{meas} D_{const} / D(t)$.

Finally, the modified SED model for the OLED degradation in digital driving can be represented by

$$L(t) = L_T D(t) \exp\left[-\left(\frac{t}{\tau_{meas}} \frac{D(t)}{D_{const}}\right)^{\beta}\right], \tag{3}$$

where L_T is the modified initial luminance according to the different initial duty ratio, and $L_T = L_0 / D_{const}$. Accordingly, the OLED luminance with respect to the duty ratio can be estimated using the modified SED model above, where the conventional SED model is a special case of the modified SED model when $D(t) = D_{const}$.

III. COMPENSATION METHOD FOR OLED DEGRADATION

Using the modified SED model, the proposed method compensates for the OLED degradation by modulating the duty ratio and maintains the OLED luminance during digital driving. Fig. 1 shows a comparison between the uncompensated and compensated OLED luminance. The compensation is discretely performed because the duty ratio is quantized according to time. D_N and $L_N(t)$ are the duty ratio and luminance of the OLED for $t_N \le t < t_{N+1}$, respectively, where $N = 0$, 1, 2, and so on. For the compensation, $D(t)$ should be discretely increased at every t_N in order to maintain the OLED luminance at $L_T D_0$. The relationship between $L_N(t)$ and D_N can be expressed as

$$\begin{aligned} L_{N+1}(t_{N+1}) / L_N(t_{N+1}) &= D_{N+1} / D_N, \quad \text{and} \\ L_N(t_N) &= L_T D_0. \end{aligned} \tag{4}$$

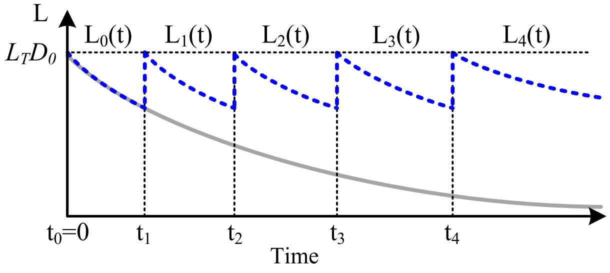

Fig. 1. Comparison between uncompensated luminance (solid line) and compensated luminance (dashed line).

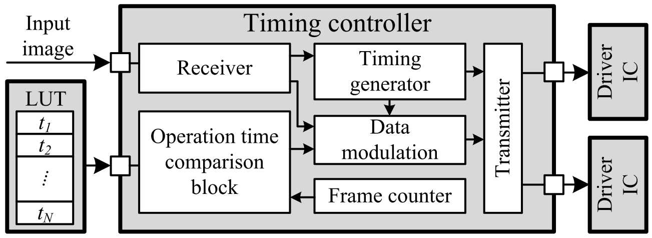

Fig. 2. Simplified block diagram of the proposed compensation method.

By combining (3) and (4), the full trajectory of the compensated $L(t)$ for $t_N \le t < t_{N+1}$ can be represented as

$$\begin{aligned} L_N(t) = L_T D_0 \exp&\left[\left(\frac{t_N}{\tau_{meas}} \frac{D_N}{D_{const}}\right)^{\beta}\right] \\ &\times \exp\left[-\left(\frac{t}{\tau_{meas}} \frac{D_N}{D_{const}}\right)^{\beta}\right]. \end{aligned} \tag{5}$$

In (5), the luminance of the OLED can be compensated by discretely increasing the duty ratio at t_N. Using (4) and (5), the recursive solution of t_N is given by

$$t_{N+1} = \left[\left(\tau_{meas} \frac{D_{const}}{D_N}\right)^{\beta} \ln\left(\frac{D_{N+1}}{D_N}\right) + t_N^{\beta}\right]^{1/\beta}. \tag{6}$$

Fig. 2 shows a simplified block diagram of the proposed compensation method. To realize the proposed compensation method, the non-volatile memory (NVM) and frame counter are used to store the look-up table (LUT) of t_N and determine the operation time of the OLED panel, respectively. The compensation is performed by comparing t_N from the LUT and the operation time of the frame counter and increasing the duty ratio when t_N is equal to the operation time. The proposed compensation method can be applied to all 256 gray levels because D(t) can be any value between 0 and 1. The operation time comparison block in Fig. 2 adjusts the operation time of the panel according to the gray levels in order to reflect a degree of OLED stress. As a result, the OLED degradation is compensated at every t_N, using simple logic blocks.

IV. EXPERIMENTAL RESULTS

As shown in Fig. 3, τ_{meas} and β of the SED model for OLED degradation are extracted from 10 samples using the digital driving pixel structure [4] of the low-temperature

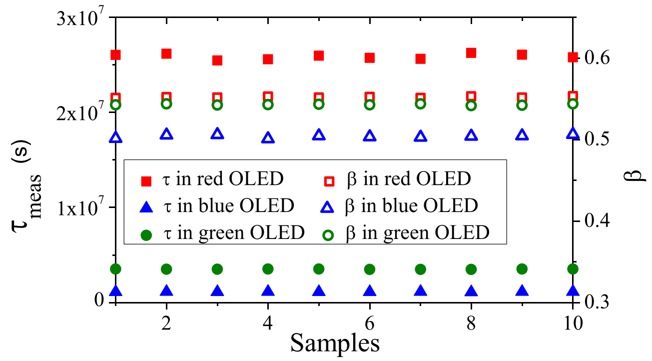

Fig. 3. τ_{meas} and β extracted from 10 samples of digital driving AMOLED panels. The average value of τ_{meas} and β are 2.92×10^7 and 0.603 for the red OLED, 3.94×10^6 and 0.560 for the green OLED, and 1.37×10^6 and 0.538 for the blue OLED, respectively.

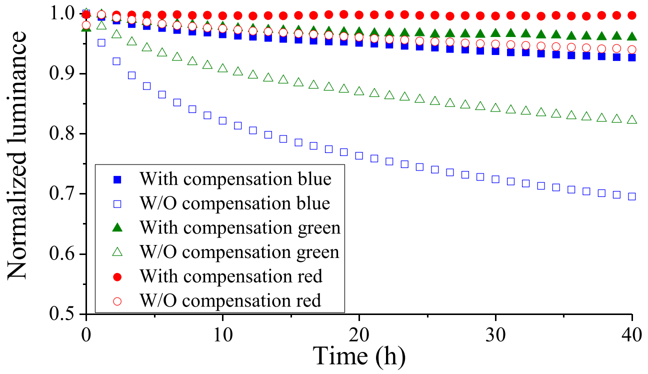

Fig. 4. Measurement result of OLED luminance with and without the proposed compensation method. After 40 hours of operation of the OLED panel, the normalized luminance with and without the proposed compensation method is 0.997 and 0.940, 0.960 and 0.822, and 0.926 and 0.696, for the red, green, and blue OLEDs, respectively.

poly-Si TFT backplane with the following measurement conditions. The maximum duty ratio is 99.94 with 1920×1080 resolution for 10 subfields at an operating frequency of 60 Hz. The maximum target luminance of the panel is 350 cd/m^2, and the power supply voltage of the red, green, and blue colors is 3.9 V, 3.8 V, and 5.8 V, respectively. An LUT for t_N is generated using the average values of τ_{meas} and β shown in Fig. 3.

To verify the proposed compensation method, six samples of digital driving panels are measured with an initial duty ratio of 0.5. The measurement results of the OLED luminance with and without the proposed compensation method are shown in Fig. 4. The estimated time to reach 50% degradation with and without the proposed compensation method is 159600 hours and 2200 hours, 5570 hours and 360 hours, and 2490 hours and 120 hours, for the red, green, and blue OLEDs, respectively. As a result, the proposed method can extend the lifetime by up to 72.5, 15.5, and 20.75 times for the red, green, and blue OLEDs, respectively, compared to the conventional digital driving method. The performance of the proposed compensation method is compared with that of the prior works and is summarized in Table I.

TABLE I

PERFORMANCE OF THE PROPOSED COMPENSATION METHOD COMPARED WITH THAT OF THE PRIOR WORKS

Index	[7]	[8]	[9]	This work	
Pixel	4T1C	4T1C	4T0.5C	3T1C	3T1C
Driving method	Analog			Digital	
Compensation	External sensing			Without compensation	With compensation
Normalized luminance	0.985	0.955	0.750	R: 0.940 G: 0.822 B: 0.696	R: 0.997 G: 0.960 B: 0.926
Test time (hour)	-	6	250	40	40

V. CONCLUSION

A compensation method for OLED degradation using digital driving is proposed. The proposed method employs the modified SED model for OLED degradation and compensates for the OLED degradation by modulating the duty ratio. The proposed model can estimate the luminance of a panel even though the duty ratio of the emission is changed during the OLED panel operation. Simple logic blocks such as NVM and frame counters are used to realize the proposed compensation method. Experimental results show that the proposed compensation method can extend the lifetime of an AMOLED panel by up to 72.5, 15.5, and 20.75 times for red, green, and blue OLEDs, respectively.

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