An ambient-light sensor system with startup correction for LTPS-TFT LCD

Ilku Nam\(^1\) and Doohyung Woo\(^2\)\(^a\)

\(^1\) Dept. of EE and also with PNU-LG Smart Control Center, Pusan National University, Busan 609–735, Korea
\(^2\) Dept. of ICEE, The Catholic University of Korea, 43-1 Yeokgok 2-dong, Wonmi-gu, Bucheon-si, Gyeonggi-do 420–743, Korea
\(a\) cowpox@catholic.ac.kr

Abstract: An ambient-light sensor system using low-temperature poly-silicon thin film transistors was studied, to reduce the power consumption of mobile applications. The proposed system with startup correction can correct the panel-to-panel variation of the ambient-light sensors, without additional equipment. The digital output of the readout circuit has 8 levels per decade for the input luminance ranges from 100 to 10000 lux, and the readout rate is 40 Hz. The proposed method provides maximum differential non-uniformity below 0.3 LSB.

Keywords: ambient-light sensor system, readout circuit, non-uniformity correction, LTPS TFT, LCD

Classification: Electron devices, circuits, and systems

References

[1] J. F. Wu, C. L. Wei, Y. T. Hsieh, C. L. Fang, H. H. Tsai and Y. Z. Juang: IEEE-PEDS Dig. Tech. Papers (2011) 944.
[2] K. Maeda, T. Nagai, T. Sakai, N. Kuwabara, S. Nishi, M. Satoh, T. Matsuo, S. Kamiya, H. Katoh, M. Ohue, Y. Kubota, H. Komiyama, T. Muramatsu, M. Katayama, P. Zebedee, S. Desumvila, C. J. Brown, H. Walton and M. Brownlow: SID symposium Digest 36 (2005) 356.
[3] H. S. Park, T. J. Ha, Y. Hong, M. K. Han, D. H. Woo, K. S. Shin and C. W. Kim: J. SID 16 (2008) 889.
[4] F. Matsuki, K. Hashimoto, K. Sano, D. Yeates, J. R. Ayres, M. Edwards and A. Steer: SID symposium Digest 38 (2007) 290.

1 Introduction

Active-matrix liquid-crystal display (AMLCD) has been widely used in mobile applications. Because an LCD panel does not illuminate for itself, the transmissive LCD uses a backlight unit (BLU), which consumes relatively large power in the mobile LCD. To reduce BLU power consumption, and to improve image visibility, there have been many efforts to control BLU brightness, based on ambient-light conditions [1, 2, 3]. Some of the ambient-light sensor (ALS) systems have been implemented
by external chips [1]. However, a monolithic system on a glass substrate is more efficient in reducing the production cost and complexity of a display module. Low-temperature poly-silicon (LTPS) thin film transistors (TFTs) can be used for a monolithic system, which integrates a photo detector, readout circuit and analog-to-digital converter (ADC) on the same glass substrate [2, 3].

A lateral PIN photo detector was fabricated by the conventional LTPS TFT process, and we measured the characteristic curve for input illuminance [3]. The LTPS photo detector shows good stability, but its panel-to-panel variation is very large. Therefore, the characteristic curve of each photo detector should be compensated by the conventional two-point correction method, as shown in Fig. 1. It is sufficient to measure each photo detector at two brightness conditions, A and B, due to their linear characteristics. Because neighboring photo detectors on the same glass show a similar characteristic curve, the dark condition (A) is commonly realized by a masked photo detector [4]. However, it is difficult to realize the bright condition (B) during the ALS system operation, so an additional test process is normally needed, and the test results should be memorized before the ALS system operation.

![Photo Current](image.png)

**Fig. 1.** Panel-to-panel variation of the LTPS photo detector, and the two-point correction method: (a) Offset correction by using dark condition (A), (b) Gain correction by using bright condition (B).

### 2 Proposed startup correction

Fig. 2 shows the proposed startup correction, which compensates for the panel-to-panel variation of the photo detector without additional testing cost and time, unlike the conventional two-point correction. The startup correction uses backlight for the bright condition, and there are three photo detectors (PD1, PD2 and PD3) on the same glass, which have similar characteristics. Because the black matrix (BM) and BLU tape cut off incident light, PD1, PD2 and PD3 sense ambient light, dark and bright condition, respectively. Fig. 2 (b) explains the integration concept of three photo currents. To realize the offset correction of Fig. 1 (a), the photo current of PD2 ($I_{\text{DARK}}$) is subtracted from the two other photo currents of PD1 ($I_{\text{PD1}}$) and PD3 ($I_{\text{PD3}}$). $I_{\text{PD}}$ ($= I_{\text{PD1}} - I_{\text{DARK}}$) and $I_{\text{BLU}}$ ($= I_{\text{PD3}} - I_{\text{DARK}}$) are
the offset corrected photo current for ambient light and bright condition, respectively. The integration period is divided into two phases. First, the backlight has an initial brightness of $L_{BLU}$, and the integrator integrates $I_{BLU}$ for the pre-defined duration of $t_{BLU}$. The integrated voltage after $t_{BLU}$ ($V_{BLU}$) is a function of the sensitivity of the photo detector ($k$), and is given by

$$V_{BLU} = \frac{k \cdot L_{BLU} \cdot t_{BLU}}{C_{INT}}$$  \hspace{1cm} (1)$$

where $C_{INT}$ is the integration capacitance. Next, the integrator is reset, and integrates $I_{PD}$ until the $t_{PD}$, when an integrating voltage reaches the $V_{BLU}$. Now, the $t_{PD}$ is given as

$$t_{PD} = \frac{C_{INT} \cdot V_{BLU}}{k \cdot L_{PD}} = \frac{t_{BLU} \cdot L_{BLU}}{L_{PD}}$$  \hspace{1cm} (2)$$

where $L_{PD}$ is the brightness of ambient light. Consequently, $t_{PD}$ is the gain corrected information for ambient light, and barely related to the sensitivity, i.e. panel-to-panel variation, because the three photo detectors on the same glass have similar characteristics.

### 3 Design of a proposed circuit

Fig. 3 and Fig. 4 show the block and timing diagram of the proposed circuit, respectively. The proposed circuit is composed of three photo detectors with four NMOS switches, an integrator, a comparator, a 9-bit counter, two registers and a 6-bit digital-to-analog converter (DAC). The 6-bit DAC is the resistor string converter with a tree-like decoder. There are four control signals ($\phi_1$, $\phi_2$, $\phi_{rst}$ and $\phi_8$), and $\phi_8$ is the main clock signal. The timing diagram is divided into three parts by $\phi_1$ and $\phi_2$, and $\phi_{rst}$ resets the integrator and counter periodically. During phase 1a, the voltage of the counter enable, $V(c)$, is kept low by $\phi_2$. Therefore, the counter maintains a

![Fig. 2. Proposed startup correction method with backlight unit: (a) Cross-sectional view of the three photo detectors, (b) Timing diagram for signal integration.](image-url)
reset level, and it is memorized at the 6-bit register. Now, the DAC output voltage, \( V(b) \), maintains its minimum value, \( V_{b1} \). The integrator integrates \( I_{\text{BLU}} = I_{\text{PD3}} - I_{\text{DARK}} \) during phase 1a, then its output voltage, \( V(a) \), reaches \( V_{\text{BLU}} \) after \( t_{\text{BLU}} \). The \( V_{\text{BLU}} \) values of each panel are different from each other, as shown in Fig 2 (b), and it should be converted to digital code to keep its value, because the backlight brightness will be controlled after phase 1a. Next, both \( \phi_1 \) and \( \phi_2 \) have low level in phase 1b, and \( V(a) \) remains as \( V_{\text{BLU}} \) ranged from \( V_{b1} \) to \( V_{b2} \). At the beginning of phase 1b, \( V(c) \) changes to high level, because the comparator output voltage is high, then the outputs of the counter, 6-bit register and \( V(b) \) increase with \( \phi_{ck} \). If \( V(b) \) begins to exceed \( V_{\text{BLU}} \), the comparator output voltage and \( V(c) \) change to low level, then the counter and DAC hold their status. At the end of phase 1b, the counter output is memorized in the 6-bit register, by changing \( \phi_1 \) to high level, and \( V(b) \) remains as \( V_{\text{BLU}} \). In the last part, phase 2, the integrator integrates \( I_{\text{PD}} = I_{\text{PD1}} - I_{\text{DARK}} \), after \( \phi_{rst} \) reset its output. The counter output also increases with \( \phi_{ck} \) after resetting, because the comparator output voltage and \( V(c) \) are low and high level at the beginning of phase 2, respectively. If \( V(a) \) begins to exceed \( V(b) \) of \( V_{\text{BLU}} \), \( V(c) \) changes to low level, then the counter holds its output, which is the digital value of the \( t_{\text{PD}} \) of Fig. 2 (b). Finally, the counter output is memorized in the 9-bit register by \( \phi_S \), and the integration and conversion cycle will go on.

**Fig. 3.** Block diagram of the readout circuit for start-up correction.

The operational amplifiers in Fig. 3 are laid out using common-centroid layout technique with large size of devices. Nevertheless, they have a large input offset voltage (\( V_{\text{OS}} \)) of a few hundred mV, because there are serious mismatches among LTPS TFTs which are mainly caused by the random distribution of grain boundaries in TFTs. However, the \( V_{\text{OS}} \) of the comparator does not affect correction accuracy because the stored \( V(b) \) after phase 1b is equal to \( V_{\text{BLU}} + V_{\text{OS}} \). The bias voltage of three photo detectors is affected by the \( V_{\text{OS}} \) of the integrator. However, PD1 and PD3 have the same bias voltage and the correction accuracy is rarely affected by the accuracy of \( I_{\text{DARK}} \) because \( I_{\text{DARK}} \) is relatively small in the reverse-biased
PN junction diode. Consequently, the proposed circuit is immune to the mismatches among LTPS TFTs.

4 Simulation results

The proposed circuit has been designed using a 4-μm 1-poly 1-metal LTPS-TFT process. The mobility (μ) and threshold voltage (V_{TH}) of n-type and p-type TFTs are extracted from the measurement data of the fabricated LTPS-TFT. The typical values of μ_n, μ_p, V_{THn}, and V_{THp} are 120 cm²/(Vs), 80 cm²/(Vs), +1.5 V, and −1.5 V, respectively. The analog circuit uses 6-V and −3-V supplies, and the digital circuit uses only 6-V supply. The maximum integration time is 23 ms, and the total power consumption is less than 150 μW, when the conversion rate is 40 Hz.

The HSPICE simulations were performed using the Rensselaer Polytechnic Institute (RPI) poly-silicon TFT model. Fig. 5 shows the simulated voltage waveforms of the proposed circuit in Fig. 3. Fig. 6 compares the simulated output of the counter using proposed startup correction with that of the counter without startup correction. We assumed that the maximum photo-response non-uniformity (PRNU) of the photo detectors on the same glass is 5% or 10%, and the panel-to-panel variation is 100%. The reference case in Fig. 6 was obtained from the photo detector with the minimum photo responsivity. On the other hand, the other three cases were obtained from the photo detectors whose photo responsivities have twice values (100% variation) of the reference case’s photo responsivity. The counter output with the startup correction has more uniform characteristics compared with that without the startup correction.

As shown in Fig. 7, the counter output is converted to the final digital code of 16 levels, in order to divide the input ambient-light luminance on the logarithmic axis, which ranges from 100 to 10000 lux, into eight sections per decade. The maximum differential non-uniformity (DNU) of the final digital code, which is similar to the differential nonlinearity (DNL), is defined as the difference between all the possible input ranges of each digital code and the ideal value. Although the panel-to-panel variation is large, the DNU of the proposed monolithic circuit with the startup correction is very low.
Fig. 5. Simulated voltage waveforms of the proposed circuit.

Fig. 6. Transfer characteristic of the counter output versus the input ambient-light luminance.

Fig. 7. Estimated maximum DNU of the final digital code.
5 Conclusion

A monolithic ambient-light sensor system with startup correction was studied, to reduce the power consumption of the mobile applications. The proposed startup correction can save additional testing cost and time, and it has a very simple structure and timing to be implemented on a glass substrate. Although we did not consider the panel-to-panel variation of the backlight luminance, which is typically less than 10%, the proposed method can instead reduce this effect because the proposed method senses the relative brightness of an ambient light to control the backlight luminance.

Acknowledgments

This research was supported by Basic Science Research Program through the National Research Foundation of Korea (NRF) funded by the Ministry of Education (NRF-2013R1A1A2011732).