New Metric For Short-Range Uniformity of AMOLEDs

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Abstract

The variations of the TFT characteristics in AMOLEDs result in the decrease of the uniformity of the displays. Measurement of the long-range uniformity (LRU) is straightforward. However, there is no method for measuring the short-range uniformity (SRU) yet. Quantifying the SRU is important in evaluating various TFT backplanes and compensation circuits. We propose new methods for measuring SRU.

1. Objectives and Background

Maintaining the uniformity has been one of the largest hurdles of active-matrix organic light emitting diode (AMOLED). The voltage-programming method employs a so-called "driving TFT" (thin-film transistor) that transfers the voltage signal at the gate to the current between the drain and the source, which eventually flows through the OLED. The variations in the TFT characteristics such as threshold voltage and mobility produce uneven current, thus uneven luminance at a given voltage.

The unevenness can be categorized into three ranges: long, mid, and short. By long-range, we mean a variation over the dimension of the display. We define a "short-range" to be a variation within one centimeter.

The major cause of short-range non-uniformity is the local and random variation of the driving TFTs. Displays with short-range non-uniformity look "sandy" [Fig. 1b]. Typical LTPS (Low Temperature Poly Silicon) process yields grains of several microns in diameter. The sizes, the growth direction, and the shape of the grains are all random and hard to control, and this randomness is the primary source of the variation in the TFT characteristics. Therefore, these LTPS backplanes usually employ compensation circuits to make the display uniform.

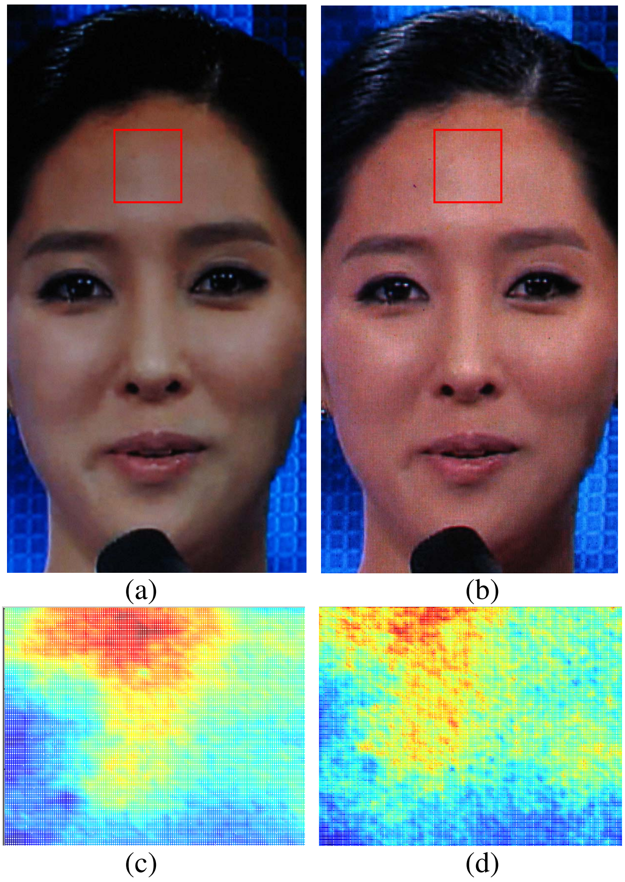

Fig. 1. Photograph of an LCD (a) and an AMOLED with poor SRU (b). The luminance map of the forehead (the red rectangle) for the LCD (c) and the AMOLED (d). The luminance variation is gentler in the LCD. On the other hand, high-frequency variations are present in the AMOLED.

The addition of the compensation circuit increases the complexity, reduces the yield, and for the case of bottom emission, decreases the aperture ratio. The compensation circuit should be minimized or simplified, while maintaining the performance for the short-range uniformity (SRU). In evaluating the performance of the circuits, the subtle difference in the SRU performance should be accurately measured. Measuring long-range uniformity (LRU) is well established. However, there is no metric for quantifying SRU. In this report, we propose two methods for measuring SRU.

2. The Min/Max Uniformity Metric

To measure SRU, one may try to measure the all, for example, one hundred individual TFT characteristics within an area, assuming that there is no short-range variation from OLED. Although the process seems straightforward, it is actually very difficult because the level of the signal is quite low and you need to distinguish between only several percentages of the difference. In our simulation, even variations as small as 5% cause the "sandiness." Even if it was possible to sense the differences, there is another problem.

The usual formula [1, 2] for uniformity is

$$Un = \%\left(1 - \frac{L_{\max} - L_{\min}}{L_{\max}}\right), \quad (1)$$

where $L_{\max}$ and $L_{\min}$ – maximum and minimum luminance in the measured area.

However, this formula is not suitable to tell the SRU since it does not take into account the luminance rippling between minimum and maximum luminance, and use only maximum and minimum luminance values of all measured points to calculate uniformity. In that way it defines value only of long range uniformity. As can be seen from Fig. 2, uniformity values of the two cases are same (maximum and minimum luminance are same). However, it is obvious that the right case will be much more "sandy."

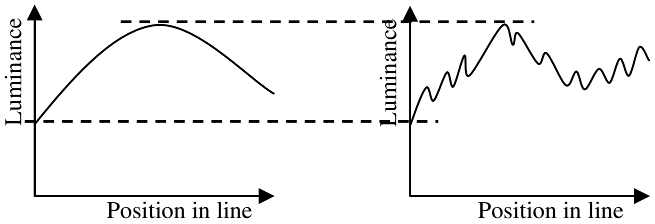

Fig. 2. Although the appearances of these two cases will be quite different, they will yield the same uniformity value.

Another way to measure the SRU is to have people evaluate the "sandiness" subjectively, using scores from 1 to 5, for example. However, this method yields poor repeatability and reproducibility. It is impossible to tell the subtle difference between various kinds of TFT backplanes and compensation circuits with this method.

3. SRU Metric #1

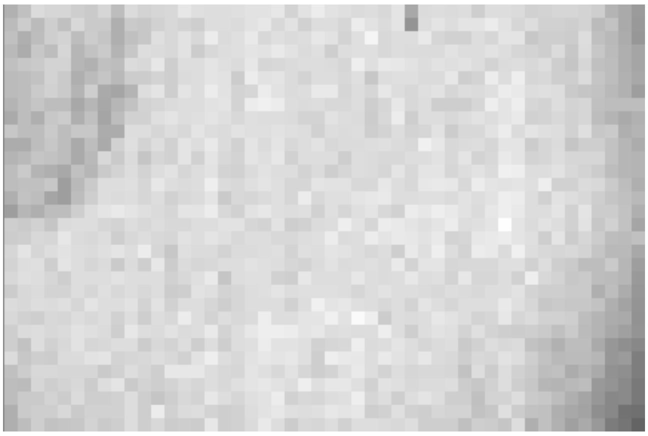

Fig. 3. The luminance map of a part (48 x 32 pixels, or 10.9 x 7.3 mm^2) in a panel captured by a 2D photo-meter.

Using a 2D photo-meter, we can measure luminance of each pixel (even subpixel) in different parts of a panel [Fig. 3]. To measure SRU from the measured 2D data, we propose the following formula:

$$Ush = \frac{\sum_{i=0}^{n-1}\sum_{j=0}^{m-1} Ur_{ij}}{n * m} \quad (2)$$

where $Ur_{ij} = 1 - \frac{L_{64\max} - L_{64\min}}{L_{64\max}}$,

$$L_{64\max} = \max_{i=0..7,\, j=0..7} L_{ij}, \quad L_{64\min} = \min_{i=0..7,\, j=0..7} L_{ij}.$$

In this formula, we calculate the uniformity value, Ur_{ij} for a sub-block of 8x8 pixels according to the Equation 1. And then the sub-block shifts by one pixel and the uniformity of the sub-block is calculated again. Each sub-block with position ij is a square with coordinates: i-3,j-3, i+4, j+4. This process is repeated until every pixel is covered. Then the averaging the individual Ur_{ij} yields Ush. The number of sub-blocks is equal to the number of pixels in the area being measured.

The results of short range uniformity measurement are presented in Fig. 4. The commercial AMOLEDs (#2 and #3) showed SRU on par with the LCD (#1).

The micro-crystalline AMOLED (#6) exhibited comparable, although slightly lower, SRU to the LCD even without the aid of a compensation circuit. The order in SRU agreed well with the human evaluation.

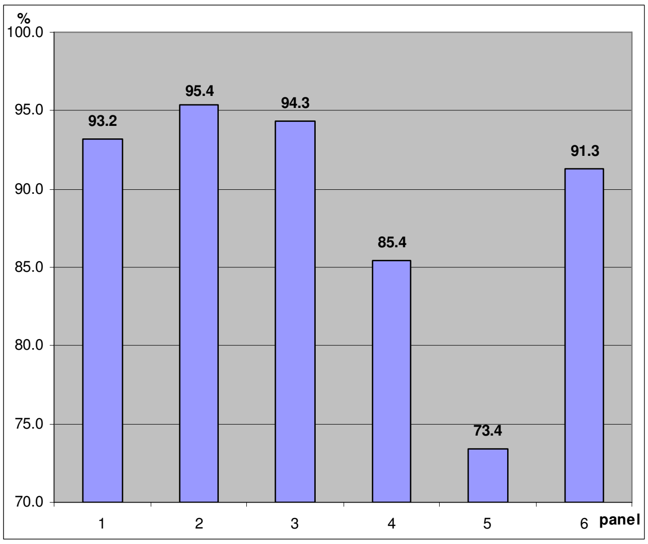

Fig. 4. Short range uniformity of different panels calculated with SRU Metric #1. Panel #1 ~ #3 are references. Panel #1 is an LCD. Panel #2 and #3 are commercial samples of AMOLEDs. Panel #4 and #5 are prototype laser-annealed AMOLEDs with different compensation circuits. Panel #6 is a prototype micro-crystalline AMOLED without compensation circuit.

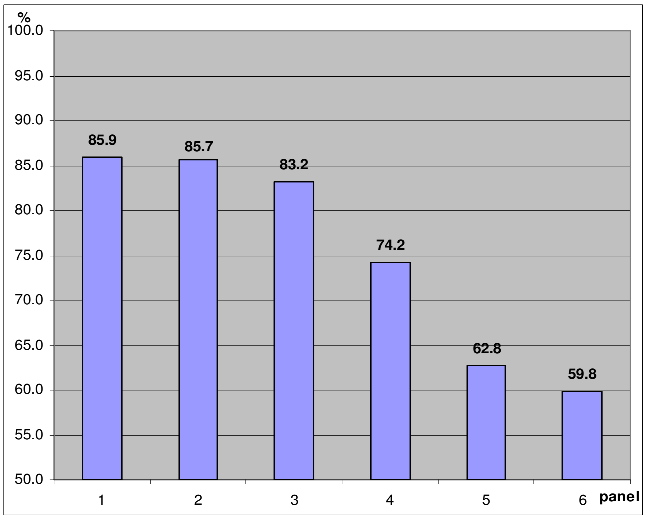

Fig. 5. The uniformity measured by the conventional Min/Max for the measured area (10.9 x 7.3 mm^2) of the panels in Fig. 4.

Equation 2 basically rejects any variation larger than 8 pixels and only calculates variance within the 8x8 sub-block. The number 8 is chosen from a matter of convenience ($8 = 2^3$ for simpler calculation, and 4 is too small and 16 is too large) rather than from strict physical grounds.

If one had naively applied the Eq. 1 for the entire measured area [Fig. 3], the result would have looked like Fig. 5. The micro-crystalline AMOLED (#6) yields the poorest score although it was judged by the human evaluators as having a very good SRU. Since the measured area is small (< 1 cm^2), one may assume that the Min/Max value may be good enough to represent the short-range uniformity. Comparison of Fig. 4 and Fig. 5 shows that it is not true.

4. SRU Metric #2

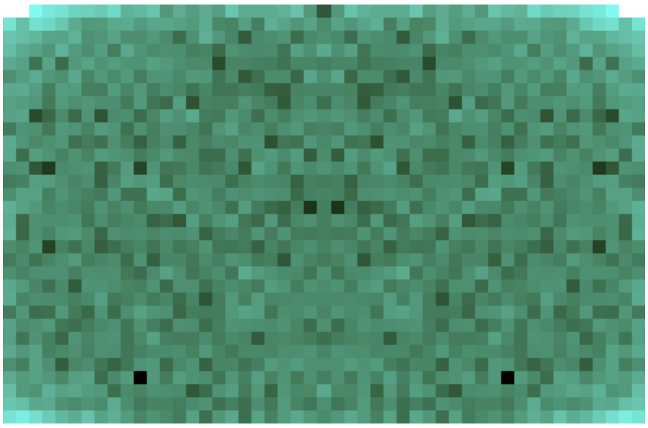

Fig. 6. Discrete Fourier Transform of Fig. 3.

Since short-range in space is equivalent to high frequency in the frequency space, we can use Fourier transform to extract the short-range uniformity. Using 2D Discrete Fourier Transformation (DFT) [3], it is possible to receive values of different frequencies of luminance fluctuations from the panel luminance measurements result [Fig. 6]. The sum of amplitudes, calculated using DFT, shows us the panel non-uniformity mostly at the short range.

To eliminate dependence from the luminance average and from the number of processed pixels, we divided this sum by F_{00} (DC component) and the number of processed pixels. Thus we receive relative value of high frequencies of luminance fluctuations at any part of the panel or full panel. Resulting formula looks as follows:

$$Uf = \frac{\sum_{i=1}^{n}\sum_{j=1}^{m} F_{ij}}{F_{00} * n * m}, (3)$$

where F_{ij} – 2D DFT result of the panel luminance measurement with size n x m at position i,j.

The high frequencies are more important for short range uniformity measurement. To increase the weight for the high frequencies and eliminate the 1/f dependence, DFT amplitudes (F_{ij}) are multiplied by the spatial frequency, or the index number (for 2D, it is a square root of the product of column and row index numbers).

$$Uf_{high} = \frac{\sum_{i=1}^{n}\sum_{j=1}^{m} \left(F_{ij} * \sqrt{i * j}\right)}{F_{00} * n * m}, (4)$$

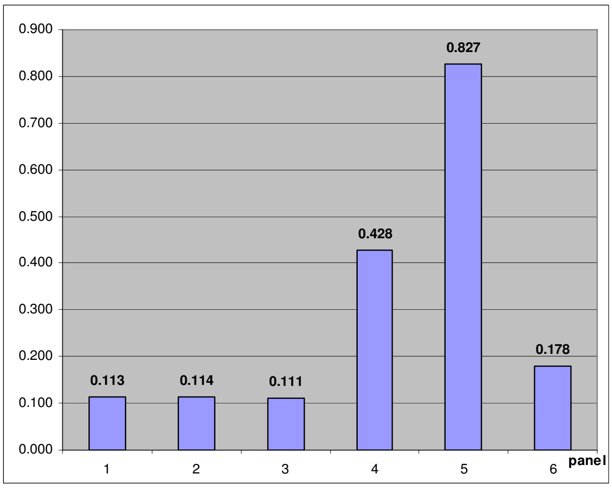

Fig. 7. Short-Range "Non-Uniformity" measured by the metric #2 (Eq. 4). Lower the better.

Fig. 7 shows the results of short range non-uniformity of the panels. The SRU metric #2 is rather a high-frequency noise power and the smaller the number is, the more uniform the panel is. On the other hand, the SRU metric #1 is uniformity and the closer it gets to 100%, the better the panel is.

The SRU metric #1 and #2 employs very different calculation methods. Nevertheless, both metrics agree well with each other about the order in the SRU for the panels measured. And the differences in the magnitudes are similar in both cases. The SRU metric #1 uses much abrupt filter (any variations shorter than 8 pixels are included with equal weight and variations larger than 8 pixels are completely eliminated). Nevertheless, at least for the panels we measured it shows equivalent distinguish ability to the SRU metric #2.

We also changed the size of the area being analyzed from 50 pixels wide to 100 and 200 pixels, to see if it affects the SRU values. The increase in the number of pixels analyzed, or the size of the area did not affect the SRU values from either of the metrics.

5. Conclusion

Measurement of SRU is important in evaluating various kinds of crystallization methods and compensation circuits for AMOLEDs. We have developed and propose two kinds of SRU metrics that can quantify the SRU of a display. Although these two methods came from very different origin, they agree well in various kinds of displays SRU appraising. These metrics are simple to measure and calculate, and we believe these can be powerful tools to develop low-cost and high-yield AMOLED panels.

6. References

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