A method of programming light emitting diode displays is provided. The method uses voltage-programming techniques wherein feedback is used for current/voltage correction.
Abstract

A method of programming light emitting diode displays is provided. The method uses voltage-programming techniques wherein feedback is used for current/voltage correction.
Voltage-Programming Scheme for Current-Driven AMOLED displays

Described below is a method for programming Active-Matrix Organic Light-Emitting Diode (AMOLED) displays. This "drive scheme" is applicable to pixel circuits in which the level of brightness is determined by the magnitude of current on the data line.

There are two fundamental concepts that are introduced in this document. One concept is to acquire the Vt shift information through a charge-and-discharge technique. The acquired Vt shift information can be used to compensate for the degradation of the pixel circuit thus maintaining uniform brightness of the display.

The second concept is to program the pixel with a current then read back the voltage necessary to maintain that current. The next time that particular level of current is required, instead of programming with a current, the pixel is programmed with the appropriate voltage. This decreases the time in which the pixel can be programmed.

This invention addresses the major issue with current-programmed pixel circuits, namely the slow programming time. The concept of using feedback to compensate the pixel circuit enhances the uniformity and stability of the display while retaining the fast programming capability of the voltage programmed drive scheme.
1. Different implementation of the Vt acquisition scheme:

There are many different methods of implementing a charge and discharge drive scheme to acquire the Vt and consecutively program the pixel circuit using a voltage-programming scheme. Three different methods of programming a pixel circuit are presented.

1.1. Charge programming

A charge programming capacitor is used to program the pixel circuit with a voltage that is equal to the sum of Vt and Vdata scaled by a constant K. The circuit is shown in Figure 1.

![Figure 1 - Charge Programming Method](image)

The constant is determined by the voltage division network formed by the charge storage capacitor and the charge coupling capacitor. During the Vt acquisition cycle, the voltage at node Idata is equal to Vt of the drive transistor and the voltage at Vdata is at ground.

When Vdata is increased from ground to the desired voltage level, the voltage at Idata is equal to (Vt+Vdata)*K.

1.2. Voltage programming though a summer

This method of voltage programming utilizes a summer to produce the programming voltage that is equal to the sum of Vt and Vdata. This circuit improves over the charge-programmed circuit by eliminating the requirement of the charge coupling capacitor Cc. By eliminating the charge coupling capacitor Cc, the accuracy of the programming voltage is improved and this method is also less susceptible to the effect of charge feed-through. A programming circuit is shown in Figure 2.
1.3. Direct digital programming

The direct digital programming method is a more complicated method of voltage programming the pixel circuit. This circuit utilizes the fact that the Vt of the drive TFT increases very slowly. Thus, Vt of the drive TFT does not have to be acquired every programming cycle, effectively hiding the Vt acquisition for the majority of the programming cycle. The Vt acquired from the pixel circuit is digitalized and stored in memory. The digital data that defines the brightness of the pixel is first added with the Vt data and the resulting voltage is then converted back to an analog value that is programmed into the pixel circuit. This programming method is designed to compensate for the slow process of Vt acquisition. For this circuit, the Vt of the pixel circuit only has to be acquired once every second or less, thus it is possible to acquire Vt for only one row of the display per frame cycle. This effectively increases the amount of time for the pixel programming cycle. The circuit to implement this programming method is shown in Figure 3.
### Summary of the different programming methods:

<table>
<thead>
<tr>
<th>Programming method</th>
<th>Advantage</th>
<th>Disadvantage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Charge programming</td>
<td>• Simple design</td>
<td>• Programming voltage affected by parasitic capacitance</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Slow programming time caused by slow V&lt;sub&gt;t&lt;/sub&gt; acquisition time</td>
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<tr>
<td></td>
<td></td>
<td>• Mismatch in charge storage capacitance can affect the programming voltage</td>
</tr>
<tr>
<td>Programming utilizing a summer</td>
<td>• Programming voltage is not affected by the parasitic capacitance</td>
<td>• More complicated circuit then the charge programmed circuit</td>
</tr>
<tr>
<td></td>
<td>• Less charge feed-through effect</td>
<td></td>
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<tr>
<td></td>
<td>• Programming voltage not affect by the charge storage capacitance</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Faster V&lt;sub&gt;t&lt;/sub&gt; acquisition time due to the elimination of the charge coupling capacitor</td>
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<tr>
<td></td>
<td>• Higher effective programming voltage due to the elimination of the voltage division network</td>
<td></td>
</tr>
<tr>
<td>Direct digital programming</td>
<td>• Fastest programming time due to less frequent need of V&lt;sub&gt;t&lt;/sub&gt; acquisition</td>
<td>• Most complicated circuit required</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• High resolution D to A converter required</td>
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</tbody>
</table>
Some circuits that can be programmed using this method:
4T current mirror:

Current programmed circuit by Yi He, Reiji Hattori and Jerzy Kanicki

2. Table lookup techniques for capturing current/voltage information

The following technique describes a technique of capturing the current/voltage correction information. When a voltage-programming scheme is utilized, the pixel circuit is programmed in an open loop configuration, where there is no feedback from the pixel circuit regarding the threshold voltage shift of the TFTs. With the current programming scheme, the brightness of the pixel remains constant over time. However, the current programming scheme is slow.

The table lookup method combines the technique of the current programming scheme with the voltage-programming scheme. The circuit can attain the compensation inherent in the current programming scheme while attaining the fast programming time that is only possible with voltage programming scheme.
The relationship between the current required to program the circuit, and the voltage necessary to obtain that programming current, is referred to as the "current/voltage correction information" or "current/voltage correction curve", or simply the "current/voltage information" or "current/voltage curve".

2.1 Building a lookup table to correct the current/voltage information

The idea is to build a correction table for every pixel in the entire display that stores a measure of the aging of each pixel. The information in the table is then combined with incoming video information (i.e. the information to be displayed) to ensure that each pixel will maintain a constant brightness over long-term use.

During the display period, the normal voltage-programming scheme is used (i.e. the voltage on the data line determines the brightness of the pixels). The voltage required to program the pixel is calculated from the pixel brightness to be displayed (from the incoming video information) combined with the correction information stored in the table. After the display has been used for a fixed period of time, the display needs to be calibrated. When the display enters calibration mode, each pixel is programmed through a current programming scheme (where the level of current on the data line determines the brightness of the pixel) and the voltage required for that current is recorded in a temporary table. The voltage required to program the pixel to the correct current is sampled at multiple current points. The multiple points can be a subset of the possible current levels (e.g. 256 possible levels for 8-bit, or 64 levels for 6-bit). This subset of voltage measurements is used to construct the correction table that is interpolated from the measurement points.

The calibration mode can be entered either through user command or can be combined with normal display mode so the calibration takes place during the display refresh period. The entire display could be calibrated at once, which would mean the display would stop showing incoming video information for a short period of time while each pixel was programmed with a current and the voltage recorded. Another option is to have a subset of the pixels calibrated, for example one pixel every fixed number of frames. This would be virtually transparent to the user, and the correction information would still be acquired for each pixel.

2.2 Combination of capturing Vt shift information with current/voltage correction information

It is possible to use the lookup table to correct the Vt shift and the current/voltage correction information at the same time. The idea combines the techniques described in Sections 1.1 to 1.3 and Section 2.1. The idea is to capture several voltage measurements at many different current points. By extending the voltage versus current curve to zero current point, the Vt shift information can be
extracted. The information is all stored in an array of tables which is applied to incoming display data.

2.3 Hidden refresh of the current/voltage correction information to compensate for Vt shift

This technique is an addition to the technique described in Section 2.1. The new current/voltage correction information is constructed while completely hidden from user's perception. The technique utilizes the information that is currently displayed on the screen (i.e. the incoming video data). By knowing the pixel characteristics from the full calibration routine that has been performed during the manufacturing process of the display, the current/voltage correction information for each pixel in the display is known. During the display's usage, the current/voltage correction curve will shift due to the change in Vt. By measuring a single point along the current/voltage correction curve (which can be the data currently displayed, that is part of the video image), a new current/voltage correction curve can be fitted to the measured point, which can be used to compensate the shift in Vt.

The process starts with the current/voltage correction curve produced during the calibration process that is done during the manufacturing of the display. A sample of this curve is shown in Figure 4.

![Current vs Voltage Graph](image)

**Figure 4 - Sample factory-calibrated current/voltage correction curve**

The next step is to measure a point along the curve. This point can be any point along the curve, so any data that the user currently has on the display can be used for calibration. This is shown in Figure 5.
Figure 5 – Sample factory current/voltage correction curve with newly measured data point

The last step is to shift the current/voltage correction curve to fit the measured point of voltage versus current relationship, this is shown in Figure 6.

Figure 6 – Sample of a new current/voltage correction curve generated from measurement of a single point

3. Further enhancement to this driving scheme

Several methods are devised to improve the display's programming speed and correction for threshold voltage shift. They are presented here.

3.1. Combined current and voltage programming technique
To enhance the circuit's ability to compensate for a change in the current/voltage curve due to temperature, threshold voltage shift, or other factors, it is desirable
to divide the pixel circuit programming into two phases. The circuit can be voltage programmed first to set the gate voltage to an approximate value, then followed by a current programming phase. The current programming phase can then fine-tune the output current.

![Figure 7 - Improved pixel driving scheme to include current programming](image)

Although the circuit shown in Figure 7 is complicated, it is faster than just current programming and has the compensation capabilities of the current programming scheme.

3.2. Extension of the direct digital programming scheme

The direct digital programming scheme can be extended to drive a 4T OLED array using voltage programmed column drivers used for driving AMLCDs (Active Matrix Liquid Crystal Display). This technique is shown in Figure 8 below.

![Figure 8 - Extended direct digital programming scheme](image)

The row and column drivers are all off-the-shelf drivers designed for AMLCD. The switching network consists of two MOSFET switches that can switch the column of the display from connecting to the column driver to the current...
source/A to D converter combination. A design for this application is shown in Figure 9.

![Switching network diagram]

**Figure 9 - Switching network**

A hidden refresh technique described in Section 2.1 and Section 2.2 is used to acquire the Vt shift information and current/voltage correction information of each pixel circuit. This current/voltage correction information is used to populate a lookup table that will then be used to compensate for the degradation in the pixel circuit that is caused by aging. The number of current programming circuits has been reduced so there is only one per display instead of one per column driver.

The MOSFET switching network can be located either off the glass in the column driver or directly on the glass using TFT switches.

The advantage of this technique is that only one current source has to be used and off-the-shelf voltage AMLCD drivers drive the rest of the display. This lowers the cost of the driver circuit and reduces the programming time for the pixel circuit.

### 3.3. Further current/voltage correction using digital feedback technique

The current/voltage information of the circuit can be further corrected by implementing the design illustrated in Figure 10.
The particular technique involves a switch that can disconnect either the top ITO (The common VDD) or the Ground and connects them into a current sensing network utilizing a high side common mode sensor similar to INA168 by TI.

During the calibration phase, each pixel is lit individually and the current consumed is acquired by the sensing network and is used to correct the table populated by the direct digital programming scheme discussed in Section 2.

A dark display current is also acquired to include the effect of dead pixel and leakage current of the array.

The amount of time required to charge and discharge the pixel can be long, which limits the frame rate.

The technique to use an A/D to convert the output to analog format can remove having to acquire Vt every programming cycle. The Vt of the pixel circuit only has to be acquired once every few minutes. Thus it is possible to acquire one column of the panel every refresh cycle.

An A/D can be large and implementing one A/D every column may be expensive.

It is possible to implement a single A/D for all the columns. However, circuit would now only acquire one pixel per frame refresh. For example, for a 320 by 240 panel, the number of pixels is 76,800. For a frame rate of 30Hz, the time required to acquire Vt from all pixels of the frame is 43 minutes. This time is still acceptable as Vt does not shift substantially in an hour.

The effect of parasitics on the programming scheme can also be considered.
The parasitics only affect the amount of time to discharge the capacitor to acquire $V_t$. Since the circuit is voltage programmed, it is not affected by the parasitics at all. And since $V_t$ is only acquired one column per frame time, it can be long. For example, for a display with 320 columns that has a frame rate of 30Hz, each frame time is 33mS. For voltage programming, it is possible to program a pixel in 70uS. For 320 columns, the time to update the display is 22mS, which still leave 11mS to complete a charge/discharge cycle.

- A method for extracting $V_t$ information from the pixel circuit which is voltage programmed.
- A method for programming AMOLED displays using current driven pixels (a “programming scheme”) that involves programming with a current, reading and storing the voltage, then subsequently programming with that voltage.
- A method of improve the current/voltage correction of the pixel circuit through feed-back technique.
- A new voltage is stored after a specified period of time.
- One method to implement (1) is to charge the pixel circuit, allow the circuit to discharge to $V_t$, then add that value to the data using a storage capacitor, as in Figure 1.
- One method to implement (2) is to build a table of current/voltage correction information for every pixel in the display as is described in Section 2.
- One method of combining the $V_t$ extraction described in section 1 with the current/voltage correction technique described in Section 2.
- One method of hiding the refresh of current/voltage correction information by using the level of pixel brightness specified by the incoming video signal to measure a single point, and then extrapolating the entire current/voltage correction curve from that point.
- One method of implement technique described in Section 1 and Section 2 and an example circuit that utilize such technique (Figure 8 and Figure 9).
- A method of implement current programmed AMOLED pixel circuit driver utilizing off-the-shelf AMLCD column driver as described in Section 3.2.
Claims:

1. A method of programming light emitting diode displays that uses voltage-programming techniques.

2. A method of programming light emitting diode displays having current driven pixels, the method comprising the steps of:
   - programming a pixel with a current;
   - reading a voltage;
   - storing the voltage; and
   - programming the pixel with the stored voltage.

3. A method of current/voltage correction of the pixel circuit using a feedback technique.

4. A method of extracting Vt information from the pixel circuit, the method comprising the steps of:
   - allowing the circuit to discharge to Vt; and
   - adding Vt to Vdata using storage capacitor.

5. A method of programming a light emitting diode the comprises the step of building a table of current/voltage correction information for each pixel fo the display.


7. A method of hiding the refreshing current/voltage correction information, the method comprising the steps of:
   - using a level of pixel brightness specified by an incoming video signal to measure a point; and
   - extrapolating a current/voltage correction curve from the point.

8. A method of implementing current programmed active matrix organic light emitting diode pixel circuit utilizing an active matrix liquid crystal display column driver.