



(11) **EP 2 404 292 B1**

(12) **EUROPEAN PATENT SPECIFICATION**

(45) Date of publication and mention
of the grant of the patent:
20.06.2018 Bulletin 2018/25

(51) Int Cl.:
G09G 3/32 (2016.01)

(21) Application number: **10706863.7**

(86) International application number:
PCT/US2010/025354

(22) Date of filing: **25.02.2010**

(87) International publication number:
WO 2010/101760 (10.09.2010 Gazette 2010/36)

(54) **ELECTROLUMINESCENT SUBPIXEL COMPENSATED DRIVE SIGNAL**
ELEKTROLUMINESZENZ-SUBPIXEL-KOMPENSIERTES ANSTEUERSIGNAL
SIGNAL DE COMMANDE COMPENSÉ POUR SOUS-PIXEL ÉLECTROLUMINESCENT

(84) Designated Contracting States:
AT BE BG CH CY CZ DE DK EE ES FI FR GB GR
HR HU IE IS IT LI LT LU LV MC MK MT NL NO PL
PT RO SE SI SK SM TR

(30) Priority: **03.03.2009 US 396662**

(43) Date of publication of application:
11.01.2012 Bulletin 2012/02

(73) Proprietor: **Global OLED Technology LLC**
Herndon, VA 20171 (US)

(72) Inventors:
• **LEVEY, Charles, I.**
Rochester, NY 14650 (US)

• **HAMER, John, W.**
Rochester, NY 14626 (US)

(74) Representative: **Gunzelmann, Rainer**
Wuesthoff & Wuesthoff
Patentanwälte PartG mbB
Schweigerstraße 2
81541 München (DE)

(56) References cited:
US-A1- 2003 057 895 US-A1- 2006 214 888
US-A1- 2006 273 997 US-A1- 2008 238 834

Note: Within nine months of the publication of the mention of the grant of the European patent in the European Patent Bulletin, any person may give notice to the European Patent Office of opposition to that patent, in accordance with the Implementing Regulations. Notice of opposition shall not be deemed to have been filed until the opposition fee has been paid. (Art. 99(1) European Patent Convention).

Description**FIELD OF THE INVENTION**

5 [0001] The present invention relates to control of a signal applied to a drive transistor for supplying current through an electroluminescent emitter.

BACKGROUND OF THE INVENTION

10 [0002] Flat-panel displays are of great interest as information displays for computing, entertainment, and communications. For example, electroluminescent (EL) emitters have been known for some years and have recently been used in commercial display devices. Such displays employ both active-matrix and passive-matrix control schemes and can employ a plurality of subpixels. Each subpixel contains an EL emitter and a drive transistor for driving current through the EL emitter. The subpixels are typically arranged in two-dimensional arrays with a row and a column address for each subpixel, and having a data value associated with the subpixel. Single EL subpixels can also be employed for lighting and user-interface applications. EL subpixels can be made using various emitter technologies, including coatable-inorganic light-emitting diode, quantum-dot, and organic light-emitting diode (OLED).

15 [0003] Electroluminescent (EL) technologies, such as organic light-emitting diode (OLED) technology, provide benefits in luminance and power consumption over other technologies such as incandescent and fluorescent lights. However, EL subpixels suffer from performance degradation over time. In order to provide a high-quality light emission over the life of a subpixel, this degradation must be compensated for.

20 [0004] The light output of an EL emitter is roughly proportional to the current through the emitter, so the drive transistor in an EL subpixel is typically configured as a voltage-controlled current source responsive to a gate-to-source voltage V_{gs} . Source drivers similar to those used in LCD displays provide the control voltages to the drive transistors. Source drivers can convert a desired code value into an analog voltage to control a drive transistor. The relationship between code value and voltage is typically non-linear, although linear source drivers with higher bit depths are becoming available. Although the nonlinear code value-to-voltage relationship has a different shape for OLEDs than the characteristic LCD S-shape (shown in e.g. U.S. Patent No. 4,896,947), the source driver electronics required are very similar between the two technologies. In addition to the similarity between LCD and EL source drivers, LCD displays and EL displays are typically manufactured on the same substrate: amorphous silicon (a-Si), as taught e.g. by Tanaka et al. in U.S. Patent No. 5,034,340. Amorphous Si is inexpensive and easy to process into large displays.

Degradation modes

35 [0005] Amorphous silicon, however, is metastable: over time, as voltage bias is applied to the gate of an a-Si TFT, its threshold voltage (V_{th}) shifts, thus shifting its I-V curve (Kagan & Andry, ed. Thin-film Transistors. New York: Marcel Dekker, 2003. Sec. 3.5, pp. 121-131). V_{th} typically increases over time under forward bias, so over time, V_{th} shift will, on average, cause a display to dim.

40 [0006] In addition to a-Si TFT instability, modern EL emitters have their own instabilities. For example, in OLED emitters, over time, as current passes through an OLED emitter, its forward voltage (V_{oled}) increases and its efficiency (typically measured in cd/A) decreases (Shinar, ed. Organic Light-Emitting Devices: a survey. New York: Springer-Verlag, 2004. Sec. 3.4, pp. 95-97). The loss of efficiency causes a display to dim on average over time, even when driven with a constant current. Additionally, in typical OLED display configurations, the OLED is attached to the source of the drive transistor. In this configuration, increases in V_{oled} will increase the source voltage of the transistor, lowering V_{gs} and thus, the current through the OLED emitter (I_{oled}), and therefore causing dimming over time.

45 [0007] These three effects (V_{th} shift, OLED efficiency loss, and V_{oled} rise) cause an OLED subpixel to lose luminance over time at a rate proportional to the current passing through that OLED subpixel. (V_{th} shift is the primary effect, V_{oled} shift the secondary effect, and OLED efficiency loss the tertiary effect.) Therefore, the subpixel must be compensated for aging to maintain a specified output over its lifetime.

Prior art

50 [0008] It has been known to compensate for one or more of the three aging effects. Considering V_{th} shift, the primary effect and one which is reversible with applied bias (Mohan et al., "Stability issues in digital circuits in amorphous silicon technology," Electrical and Computer Engineering, 2001, Vol. 1, pp. 583-588), compensation schemes are generally divided into four groups: in-pixel compensation, in-pixel measurement, in-panel measurement, and reverse bias.

[0009] In-pixel V_{th} compensation schemes add additional circuitry to the subpixel to compensate for the V_{th} shift as it happens. For example, Lee et al., in "A New a-Si:H TFT Pixel Design Compensating Threshold Voltage Degradation of

TFT and OLED", SID 2004 Digest, pp. 264-274, teach a seven-transistor, one-capacitor (7T1C) subpixel circuit which compensates for V_{th} shift by storing the V_{th} of the subpixel on that subpixel's storage capacitor before applying the desired data voltage.. Methods such as this compensate for V_{th} shift, but they cannot compensate for V_{oled} rise or OLED efficiency loss. These methods require increased subpixel complexity and increased subpixel electronics size compared to the conventional 2T1C voltage-drive subpixel circuit. Increased subpixel complexity reduces yield, because the finer features required are more vulnerable to fabrication errors. Particularly in typical bottom-emitting configurations, increased total size of the subpixel electronics increases power consumption because it reduces the aperture ratio, the percentage of the subpixel which emits light. Light emission of an OLED is proportional to area at a fixed current, so an OLED emitter with a smaller aperture ratio requires more current to produce the same luminance as an OLED with a larger aperture ratio. Additionally, higher currents in smaller areas increase current density in the OLED emitter, which accelerates V_{oled} rise and OLED efficiency loss.

[0010] In-pixel measurement V_{th} compensation schemes add additional circuitry to each subpixel to allow values representative of V_{th} shift to be measured. Off-panel circuitry then processes the measurements and adjusts the drive of each subpixel to compensate for V_{th} shift. For example, Nathan et al., in U.S. Patent Application Publication No. 2006/0273997, teach a four-transistor pixel circuit which allows TFT degradation data to be measured as either current under given voltage conditions or voltage under given current conditions. Nara et al., in U.S. Patent No. 7,199,602, teach adding a switching transistor to the subpixel to connect it to an inspection interconnect. Kimura et al., in U.S. Patent No. 6,518,962, teach adding correction TFTs to the subpixel to compensate for EL degradation. These methods share the disadvantages of in-pixel V_{th} compensation schemes, but some can additionally compensate for V_{oled} shift or OLED efficiency loss.

[0011] In-pixel measurement V_{th} compensation schemes add circuitry around a panel to take and process measurements without modifying the design of the panel. For example, Naugler et al., in U.S. Patent Application Publication No. 2008/0048951, teach measuring the current through an OLED emitter at various gate voltages of a drive transistor to locate a point on precalculated lookup tables used for compensation. However, this method requires a large number of lookup tables, consuming a significant amount of memory. Further, this method does not recognize the problem of integrating compensation with image processing typically performed in display drive electronics.

[0012] Reverse-bias V_{th} compensation schemes use some form of reverse voltage bias to shift V_{th} back to some starting point. These methods cannot compensate for V_{oled} rise or OLED efficiency loss. For example, Lo et al., in U.S. Patent No. 7,116,058, teach modulating the reference voltage of the storage capacitor in an active-matrix pixel circuit to reverse-bias the drive transistor between each frame. Applying reverse-bias within or between frames prevents visible artifacts, but reduces duty cycle and thus peak brightness. Reverse-bias methods can compensate for the average V_{th} shift of the panel with less increase in power consumption than in-pixel compensation methods, but they require more complicated external power supplies, can require additional pixel circuitry or signal lines, and may not compensate individual subpixels that are more heavily faded than others.

[0013] Considering V_{oled} shift and OLED efficiency loss, U.S. Patent No. 6,995,519 by Arnold et al. is one example of a method that compensates for aging of an OLED emitter. This method assumes that the entire change in emitter luminance is caused by changes in the OLED emitter. However, when the drive transistors in the circuit are formed from a-Si, this assumption is not valid, as the threshold voltage of the transistors also changes with use. The method of Arnold will thus not provide complete compensation for subpixel aging in circuits wherein transistors show aging effects. Additionally, when methods such as reverse bias are used to mitigate a-Si transistor threshold voltage shifts, compensation of OLED efficiency loss can become unreliable without appropriate tracking/prediction of reverse bias effects, or a direct measurement of the OLED voltage change or transistor threshold voltage change.

[0014] Alternative methods for compensation measure the light output of the subpixel directly, as taught e.g. by Young et al. in U.S. Patent No. 6,489,631. Such methods can compensate for changes in all three aging factors, but require either a very high-precision external light sensor, or an integrated light sensors in the subpixel. An external light sensor adds to the cost and complexity of a device, while integrated light sensors increase subpixel complexity and electronics size, with attendant performance reductions.

[0015] US Patent Application US 2003/0057895 A1 discloses a driving transistor provided in a pixel and corrects a video signal to be inputted to the pixel based on the specification. As a result, a light emitting device is provided in which influence of fluctuation in characteristic among transistors is removed to obtain clear multi-gray scale. A light emitting device is also provided, in which a change with age in amount of current flowing between two electrodes of a light emitting element is reduced to obtain clear multi-gray scale display.

[0016] US Patent Application US 2006/0214888 A1 discloses a circuit arrangement for the ageing compensation of an organic light-emitting diode (OLED) which is fed from a supply voltage and is switched by means of a driver transistor operated in saturation operation, by means of a driving of the light-emitting diode. The method comprises the following steps of: storing at least one desired current-voltage value pair of a desired current-voltage characteristic curve of the light-emitting diode; transferring the driver transistor from saturation operation to linear operation during a measurement cycle; measuring a current value for the current through the light-emitting diode by means of a current measuring circuit

in the measurement cycle; determining at least one present current-voltage value pair of a present current-voltage characteristic curve of the light-emitting diode by means of the measured current value; comparing the at least one present current-voltage value pair of the light-emitting diode with the desired current-voltage value pair of the light-emitting diode; and generating driving parameters for driving the light-emitting diode in a manner dependent on the result of the comparison.

[0017] There is a continuing need, therefore, for improving compensation to overcome these objections to compensate for EL subpixel degradation.

SUMMARY OF THE INVENTION

[0018] The present invention provides an apparatus for providing a drive transistor control signal to a gate electrode of a drive transistor in an electroluminescent (EL) subpixel in accordance with claim 1.

[0019] The present invention provides an effective way of providing the drive transistor control signal. It requires only one measurement to perform compensation. It can be applied to any active-matrix subpixel. The compensation of the control signal has been simplified by using a look-up table (LUT) to change signals from nonlinear to linear so compensation can be in linear voltage domain. It compensates for V_{th} shift, Voled shift, and OLED efficiency loss without requiring complex pixel circuitry or external measurement devices. It does not decrease the aperture ratio of a subpixel. It has no effect on the normal operation of the subpixel. Improved S/N (signal/noise) is obtained by taking measurements of the characteristics of the EL subpixel while operating in the linear region of transistor operation.

BRIEF DESCRIPTION OF THE DRAWINGS

[0020]

FIG. 1 is a block diagram of a display system for practicing the present invention;
 FIG. 2 is a schematic of a detailed version of the block diagram of FIG. 1;
 FIG. 3 is a timing diagram for operating the measurement circuit of FIG. 2;
 FIG. 4A is a representative I-V characteristic curve of un-aged and aged subpixels, showing V_{th} shift;
 FIG. 4B is a representative I-V characteristic curve of un-aged and aged subpixels, showing V_{th} and V_{oled} shift;
 FIG. 5A is a high-level dataflow diagram of the compensator of FIG. 1;
 FIG. 5B is part one (of two) of a detailed dataflow diagram of the compensator;
 FIG. 5C is part two (of two) of a detailed dataflow diagram of the compensator;
 FIG. 6 is a Jones-diagram representation of the effect of a domain-conversion unit and a compensator;
 FIG. 7 is a representative plot showing frequency of compensation measurements over time;
 FIG. 8 is a representative plot showing percent efficiency as a function of percent current;
 FIG. 9 is a detailed schematic of a subpixel according to the present invention;
 FIG. 10 is a plot of improvements in OLED voltage over time; and FIG. 11 is a graph showing the relationship between OLED efficiency, OLED age, and OLED drive current density.

DETAILED DESCRIPTION OF THE INVENTION

[0021] The present invention compensates for degradation in the drive transistors and electroluminescent (EL) emitters of an EL subpixel, such as an organic light-emitting diode (OLED) subpixel. In one embodiment, it compensates for V_{th} shift, V_{oled} shift, and OLED efficiency loss of all subpixels on an active-matrix OLED panel.

[0022] The discussion to follow first considers the system as a whole. It then proceeds to the electrical details of a subpixel, followed by the electrical details for measuring the subpixel. It next covers how the compensator uses measurements. Finally, it describes how this system is implemented in one embodiment, e.g. in a consumer product, from the factory to end-of-life.

Overview

[0023] FIG. 1 shows a block diagram of a system 10 of the present invention. A nonlinear input signal 11 commands a particular light intensity from an EL emitter in an EL subpixel. This signal 11 can come from a video decoder, an image processing path, or another signal source, can be digital or analog, and can be nonlinearly-or linearly-coded. For example, the nonlinear input signal can be an sRGB code value (IEC 61966-2-1:1999+A1) or an NTSC luma voltage. Whatever the source and format, the signal can preferentially be converted into a digital form and into a linear domain, such as linear voltage, by a converter 12, which will be discussed further in "Cross-domain processing, and bit depth", below. The result of the conversion will be a linear code value, which can represent a commanded drive voltage.

[0024] A compensator 13 receives the linear code value, which can correspond to the particular light intensity commanded from the EL subpixel. As a result of variations in the drive transistor and EL emitter caused by mura and by operation of the drive transistor and EL emitter in the EL subpixel over time, the EL subpixel will generally not produce the commanded light intensity in response to the linear code value. The compensator 13 outputs a changed linear code value that will cause the EL subpixel to produce the commanded intensity, thereby compensating for variations in the characteristics of the drive transistor and EL emitter caused by operation of the drive transistor and EL emitter over time, and for variations in the characteristics of the drive transistor and EL emitter from subpixel to subpixel. The operation of the compensator will be discussed further in "Implementation," below.

[0025] The changed linear code value from the compensator 13 is passed to a source driver 14 which can be a digital-to-analog converter. The source driver 14 produces a drive transistor control signal, which can be an analog voltage or current, or a digital signal such as a pulse-width-modulated waveform, in response to the changed linear code value. In a preferred embodiment, the source driver 14 can be a source driver having a linear input-output relationship, or a conventional LCD or OLED source driver with its gamma voltages set to produce an approximately linear output. In the latter case, any deviations from linearity will affect the quality of the results. The source driver 14 can also be a time-division (digital-drive) source driver, as taught e.g. in commonly assigned WO 2005/116971 by Kawabe. The analog voltage from a digital-drive source driver is set at a predetermined level commanding light output for an amount of time dependent on the output signal from the compensator. A conventional source driver, by contrast, provides an analog voltage at a level dependent on the output signal from the compensator for a fixed amount of time (generally the entire frame). A source driver can output one or more drive transistor control signals simultaneously. A panel preferably has a plurality of source drivers, each outputting the drive transistor control signal for one subpixel at a time.

[0026] The drive transistor control signal produced by the source driver 14 is provided to an EL subpixel 15. This circuit, as will be discussed in "Display element description," below. When the analog voltage is provided to the gate electrode of the drive transistor in the EL subpixel 15, current flows through the drive transistor and EL emitter, causing the EL emitter to emit light. There is generally a linear relationship between current through the EL emitter and luminance of the light output of the emitter, and a nonlinear relationship between voltage applied to the drive transistor and current through the EL emitter. The total amount of light emitted by an EL emitter during a frame can thus be a nonlinear function of the voltage from the source driver 14.

[0027] The current flowing through the EL subpixel is measured under specific drive conditions by a current-measurement circuit 16, as will be discussed further in "Data collection," below. The measured current for the EL subpixel provides the compensator with the information it needs to adjust the commanded drive signal. This will be discussed further in "Algorithm," below.

Display element description

[0028] FIG. 9 shows an EL subpixel 15 that applies current to an EL emitter, such as an OLED emitter, and associated circuitry. EL subpixel 15 includes a drive transistor 201, an EL emitter 202, and optionally a storage capacitor 1002 and a select transistor 36. A first voltage supply 211 ("PVDD") can be positive, and a second voltage supply 206 ("Vcom") can be negative. The EL emitter 202 has a first electrode 207 and a second electrode 208. The drive transistor has a gate electrode 203, a first supply electrode 204 which can be the drain of the drive transistor, and a second supply electrode 205 which can be the source of the drive transistor. A drive transistor control signal can be provided to the gate electrode 203, optionally through a select transistor 36. The drive transistor control signal can be stored in storage capacitor 1002. The first supply electrode 204 is electrically connected to the first voltage supply 211. The second supply electrode 205 is electrically connected to the first electrode 207 of the EL emitter 202 to apply current to the EL emitter. The second electrode 208 of the EL emitter is electrically connected to the second voltage supply 206. The voltage supplies are typically located off the EL panel. Electrical connection can be made through switches, bus lines, conducting transistors, or other devices or structures capable of providing a path for current.

[0029] In one embodiment of the present invention, first supply electrode 204 is electrically connected to first voltage supply 211 through a PVDD bus line 1011, second electrode 208 is electrically connected to second voltage supply 206 through a sheet cathode 1012, and the drive transistor control signal is provided to gate electrode 203 by a source driver 14 across a column line 32 when select transistor 36 is activated by a gate line 34.

[0030] FIG. 2 shows the EL subpixel 15 in the context of the system 10, including nonlinear input signal 11, converter 12, compensator 13, and source driver 14 as shown in FIG. 1. As described above, the drive transistor 201 has gate electrode 203, first supply electrode 204 and second supply electrode 205. The EL emitter 202 has first electrode 207 and second electrode 208. The system has voltage supplies 211 and 206.

[0031] Neglecting leakage, the same current, the drive current, passes from first voltage supply 211, through the first supply electrode 204 and the second supply electrode 205, through the EL emitter electrodes 207 and 208, to the second voltage supply 206. The drive current is what causes the EL emitter to emit light. Therefore, current can be measured at any point in this drive current path. Current can be measured off the EL panel at the first voltage supply 211 to reduce

the complexity of the EL subpixel. Drive current is referred to herein as I_{ds} , the current through the drain and source terminals of the drive transistor.

Data collection

Hardware

[0032] Still referring to FIG. 2, to measure the current of the EL subpixel 15 without relying on any special electronics on the panel, the present invention employs a measuring circuit 16 including a current mirror unit 210, a correlated double-sampling (CDS) unit 220, and optionally an analog-to-digital converter (ADC) 230 and a status signal generation unit 240.

[0033] The EL subpixel 15 is measured at a current corresponding to a measurement reference gate voltage (FIG. 4A 510) on the gate electrode 203 of drive transistor 201. To produce this voltage, when taking measurements, source driver 14 acts as a test voltage source and provides the measurement reference gate voltage to gate electrode 203. Measurements can be advantageously kept invisible to the user by selecting a measurement reference gate voltage which corresponds to a measured current which is less than a selected threshold current. The selected threshold current can be chosen to be less than that required to emit appreciable light from an EL emitter, e.g. 1.0 nit or less. Since measured current is not known until the measurement is taken, the measurement reference gate voltage can be selected by modelling to correspond to an expected current which is a selected headroom percentage below the selected threshold current.

[0034] The current mirror unit 210 is attached to voltage supply 211, although it can be attached anywhere in the drive current path. A first current mirror 212 supplies drive current to the EL subpixel 15 through a switch 200, and produces a mirrored current on its output 213. The mirrored current can be equal to the drive current, or a function of the drive current. For example, the mirrored current can be a multiple of the drive current to provide additional measurement-system gain. A second current mirror 214 and a bias supply 215 apply a bias current to the first current mirror 212 to reduce the impedance of the first current mirror viewed from the panel, advantageously increasing the response speed of the measurement circuit. This circuit also reduces changes in the current through the EL subpixel being measured due to voltage changes in the current mirror resulting from current draw of the measurement circuit. This advantageously improves signal-to-noise ratio over other current-measurement options, such as a simple sense resistor, which can change voltages at the drive transistor terminals depending on current. Finally, a current-to-voltage (1-to-V) converter 216 converts the mirrored current from the first current mirror into a voltage signal for further processing. The 1-to-V converter 216 can include a transimpedance amplifier or a low-pass filter.

[0035] Switch 200, which can be a relay or FET, can selectively electrically connect the measuring circuit to the drive current flow through the first and second electrodes of the drive transistor 201. During measurement, the switch 200 can electrically connect first voltage supply 211 to first current mirror 212 to permit measurements. During normal operation, the switch 200 can electrically connect first voltage supply 211 directly to first supply electrode 204 rather than to first current mirror 212, thus removing the measuring circuit from the drive current flow. This causes the measurement circuitry to have no effect on normal operation of the panel. It also advantageously permits the measurement circuit's components, such as the transistors in the current mirrors 212 and 214, to be sized only for measurement currents and not for operational currents. As normal operation generally draws much more current than measurement, this permits substantial reduction in the size and cost of the measurement circuit.

Sampling

[0036] The current mirror unit 210 permits measurement of the current for one EL subpixel at a single point in time. To improve signal-to-noise ratio, in one embodiment the present invention uses correlated double-sampling.

[0037] Referring now to FIG. 3, and also to FIG. 2, a measurement 49 is taken when the EL subpixel 15 is off. It is thus drawing a dark current, which can be zero or only a leakage amount. If the dark current is nonzero, it can preferably be deconfounded with the measurement of the current of the EL subpixel 15. At time 1, the EL subpixel 15 is activated and its current 41 measured with measuring circuit 16. Specifically, what is measured is the voltage signal from the current-mirror unit 210, which represents the drive current I_{ds} through the first and second voltage supplies as discussed above; measuring the voltage signal representing current is referred to as "measuring current" for clarity. Current 41 is the sum of the current from the first subpixel and the dark current. A difference 43 between the first measurement 41 and the dark-current measurement 49 is the current drawn by the second subpixel. This method permits measurements to be taken as fast as the settling time of a subpixel will permit.

[0038] Referring back to FIG. 2, and also to FIG. 3, correlated double-sampling unit 220 samples the measured currents to produce status signals. In hardware, currents are measured by latching their corresponding voltage signals from current mirror unit 210 into sample-and-hold units 221 and 222 of FIG. 2. The voltage signals can be those produced

by I-to-V converter 216. A differential amplifier 223 takes the differences between successive subpixel measurements. The output of sample-and-hold unit 221 is electrically connected to the positive terminal of differential amplifier 223 and the output of unit 222 is electrically connected to the negative terminal of amplifier 223. For example, when current 49 is measured, the measurement is latched into sample-and-hold unit 221. Then, before current 41 is measured (latched into unit 221), the output of unit 221 is latched into second sample-and-hold unit 222. Current 41 is then measured. This leaves current 49 in unit 222 and current 41 in unit 221. The output of the differential amplifier, the value in unit 221 minus the value in unit 222, is thus (the voltage signal representing) current 41 minus (the voltage signal representing) current 49, or difference 43. Measurements can successively be taken at a variety of drive levels (gate voltages or current densities) to form I-V curves for the subpixel.

[0039] The analog or digital output of differential amplifier 223 can be provided directly to compensator 13. Alternatively, analog-to-digital converter 230 can preferably digitize the output of differential amplifier 223 to provide digital measurement data to compensator 13.

[0040] The measuring circuit 16 can preferably include a status signal generation unit 240 which receives the output of differential amplifier 223 and performs further processing to provide the status signal for the EL subpixel. Status signals can be digital or analog. Referring to FIG. 5B, status signal generation unit 240 is shown in the context of compensator 13 for clarity. In various embodiments, status signal generation unit 240 can include a memory 619 for holding data about the subpixel.

[0041] In a first embodiment of the present invention, the current difference, e.g. 43, can be the status signal for a corresponding subpixel. In this embodiment the status signal generation unit 240 can perform a linear transform on current difference, or pass it through unmodified. The current through the subpixel (43) at the measurement reference gate voltage depends on, and thus meaningfully represents, the characteristics of the drive transistor and EL emitter in the subpixel. The current difference 43 can be stored in memory 619.

[0042] In a second embodiment, memory 619 stores a target signal i_0 611 for the EL subpixel 15. Memory 619 also stores a most recent current measurement i_1 612 of the EL subpixel, which can be the value most recently measured by the measurement circuit for the subpixel. Measurement 612 can also be an average of a number of measurements, an exponentially-weighted moving average of measurements over time, or the result of other smoothing methods which will be obvious to those skilled in the art. Target signal i_0 611 and current measurement i_1 612 can be compared as described below to provide a percent current 613, which can be the status signal for the EL subpixel. The target signal for the subpixel can be a current measurement of the subpixel and thus percent current can represent variations in the characteristics of the drive transistor and EL emitter caused by operation of the drive transistor and EL emitter over time.

[0043] Memory 619 can include RAM, nonvolatile RAM, such as a Flash memory, and ROM, such as EEPROM. In one embodiment, the i_0 value is stored in EEPROM and the i_1 value is stored in Flash.

Sources of noise

[0044] In practice, the current waveform can be other than a clean step, so measurements can be taken only after waiting for the waveform to settle. Multiple measurements of each subpixel can also be taken and averaged together. Such measurements can be taken consecutively, or in separate measurement passes. Capacitance between voltage supplies 206 and 211 can add to the settling time. This capacitance can be intrinsic to the panel or provided by external capacitors, as is common in normal operation. It can be advantageous to provide a switch that can be used to electrically disconnect the external capacitors while taking measurements.

[0045] Noise on any voltage supply will affect the current measurement. For example, noise on the voltage supply which the gate driver uses to deactivate rows (often called VGL or Voff, and typically around -8VDC) can capacitively couple across the select transistor into the drive transistor and affect the current, thus making current measurements noisier. If a panel has multiple power-supply regions, for example a split supply plane, those regions can be measured in parallel. Such measurement can isolate noise between regions and reduce measurement time.

[0046] Whenever the source driver switches, its noise transients can couple into the voltage supply planes and the individual subpixels, causing measurement noise. To reduce this noise, the control signals out of the source driver can be held constant. This will eliminate source-driver transient noise.

Current stability

[0047] This discussion so far assumes that once the subpixel is turned on and settles to some current, it remains at that current for the remainder of the column. Two effects that can violate that assumption are storage-capacitor leaking and within-subpixel effects.

[0048] Referring to FIG. 9, leakage current of select transistor 36 in subpixel 15 can gradually bleed off charge on storage capacitor 1002, changing the gate voltage of drive transistor 201 and thus the current drawn. Additionally, if column line 32 is changing value over time, it has an AC component, and therefore can couple through the parasitic

capacitances of the select transistor onto the storage capacitor, changing the storage capacitor's value and thus the current drawn by the subpixel.

[0049] Even when the storage capacitor's value is stable, within-subpixel effects can corrupt measurements. A common within-subpixel effect is self-heating of the subpixel, which can change the current drawn by the subpixel over time. The drift mobility of an a-Si TFT is a function of temperature; increasing temperature increases mobility (Kagan & Andry, op. cit., sec. 2.2.2, pp. 42-43). As current flows through the drive transistor, power dissipation in the drive transistor and in the EL emitter will heat the subpixel, increasing the temperature of the transistor and thus its mobility. Additionally, heat lowers V_{oled} ; in cases where the OLED is attached to the source terminal of the drive transistor, this can increase V_{gs} of the drive transistor. These effects increase the amount of current flowing through the transistor. Under normal operation, self-heating can be a minor effect, as the panel can stabilize to an average temperature based on the average contents of the image it is displaying. However, when measuring subpixel currents, self-heating can corrupt measurements.

[0050] To correct for self-heating effects and any other within-subpixel effects producing similar noise signatures, the self-heating can be characterized and subtracted off the known self-heating component of each subpixel.

[0051] Error due to self-heating, and power dissipation, can be reduced by selecting a lower measurement reference gate voltage (FIG. 4A 510), but a higher voltage improves signal-to-noise ratio. Measurement reference gate voltage can be selected for each panel design to balance these factors.

Algorithm

[0052] Referring to FIG. 4A, I-V curve 501 is a measured characteristic of a subpixel before aging. I-V curve 502 is a measured characteristic of that subpixel after aging. Curves 501 and 502 are separated by what is largely a horizontal shift, as shown by identical voltage differences 503, 504, 505, and 506 at different current levels. That is, the primary effect of aging is to shift the I-V curve on the gate voltage axis by a constant amount. This is in keeping with the MOSFET saturation-region drive transistor equation, $I_d = K(V_{gs} - V_{th})^2$ (Lurch, N. Fundamentals of electronics, 2e. New York: John Wiley & Sons, 1971, pg. 110): the drive transistor is operated, V_{th} increases; and as V_{th} increases, V_{gs} increases correspondingly to maintain I_d constant. Therefore, constant V_{gs} leads to lower I_{ds} as V_{th} increases.

[0053] At the measurement reference gate voltage 510, the un-aged subpixel produced the current represented at point 511. The aged sub-pixel, however, produces at that gate voltage the lower amount of current represented at point 512a. Points 511 and 512a can be two measurements of the same subpixel taken at different times. For example, point 511 can be a measurement at manufacturing time, and point 512a can be a measurement after some use by a customer. The current represented at point 512a would have been produced by the un-aged subpixel when driven with voltage 513 (point 512b), so a voltage shift ΔV_{th} 514 is calculated as the voltage difference between voltages 510 and 513. Voltage shift 514 is thus the shift required to bring the aged curve back to the unaged curve. In this example, ΔV_{th} 514 is just under two volts. Then, to compensate for the V_{th} shift, and drive the aged subpixel to the same current as the un-aged subpixel had, voltage difference 514 is added to every commanded drive voltage (linear code value). For further processing, percent current is also calculated as current 512a divided by current 511. An unaged subpixel will thus have 100% current. Percent current is used in several algorithms according to the present invention. Any negative current reading 511, such as might be caused by extreme environmental noise, can be clipped to 0, or disregarded. Note that percent current is always calculated at the measurement reference gate voltage 510.

[0054] In general, the current of an aged subpixel can be higher or lower than that of an un-aged subpixel. For example, higher temperatures cause more current to flow, so a lightly-aged subpixel in a hot environment can draw more current than an unaged subpixel in a cold environment. The compensation algorithm of the present invention can handle either case; ΔV_{th} 514 can be positive or negative (or zero, for unaged pixels). Similarly, percent current can be greater or less than 100% (or exactly 100%, for unaged pixels).

[0055] Since the voltage difference due to V_{th} shift is the same at all currents, any single point on the I-V curve can be measured to determine that difference. In one embodiment, measurements are taken at high gate voltages, advantageously increasing signal-to-noise ratio of the measurements, but any gate voltage on the curve can be used.

[0056] V_{oled} shift is the secondary aging effect. As the EL emitter is operated, V_{oled} shifts, causing the aged I-V curve to no longer be a simple shift of the un-aged curve. This is because V_{oled} rises nonlinearly with current, so V_{oled} shift will affect high currents differently than low currents. This effect causes the I-V curve to stretch horizontally as well as shifting. To compensate for V_{oled} shift, two measurements at different drive levels can be taken to determine how much the curve has stretched, or the typical V_{oled} shift of OLEDs under load can be characterized to permit estimation of V_{oled} contribution in an open-loop manner. Both can produce acceptable results.

[0057] Referring to FIG. 4B, an unaged-subpixel I-V curve 501 and an aged-subpixel I-V curve 502 are shown on a semilog scale. Components 550 are due to V_{th} shift and components 552 are due to V_{oled} shift. V_{oled} shift can be characterized by driving an instrumented OLED subpixel with a typical input signal for a long period of time, and periodically measuring V_{th} and V_{oled} . The two measurements can be made separately by providing a probe point on the instrumented subpixel between the OLED and the transistor. Using this characterization, percent current can be mapped to an ap-

appropriate ΔV_{th} and ΔV_{oled} , rather than to a V_{th} shift alone.

[0058] In one embodiment, the EL emitter 202 (FIG. 9) is connected to the source terminal of the drive transistor 201. Any change in V_{oled} thus has a direct effect on I_{ds} , as it changes the voltage V_s at the source terminal of the drive transistor and thus V_{gs} of the drive transistor.

[0059] In a preferred embodiment, the EL emitter 202 is connected to the drain terminal of the drive transistor 201, for example, in PMOS non-inverted configurations, in which the OLED anode is tied to the drive transistor drain. V_{oled} rise thus changes V_{ds} of the drive transistor 201, as the OLED is connected in series with the drain-source path of the drive transistor. Modern OLED emitters, however, have much smaller ΔV_{oled} than older emitters for a given amount of aging, reducing the magnitude of V_{ds} change and thus of I_{ds} change.

[0060] FIG. 10 shows a plot of the typical voltage rise ΔV_{oled} for a white OLED over its lifetime (until T50, 50% luminance, measured at 20mA/cm²). This plot shows the reduction in ΔV_{oled} as OLED technology has improved. This reduced ΔV_{oled} reduces V_{ds} change. Referring to FIG. 4A, current 512a for an aged subpixel will be much closer to current 511 for a modern OLED emitter with a smaller ΔV_{oled} than it will for an older emitter with a larger ΔV_{oled} . Therefore, much more sensitive current measurements can be required for modern OLED emitters than for older emitters. However, more sensitive measurement hardware can be expensive.

[0061] The requirement for extra measurement sensitivity can be mitigated by operating the drive transistor in the linear region of operation while taking current measurements. As is known in the electronics art, thin-film transistors conduct appreciable current in two different modes of operation: linear ($V_{ds} < V_{gs} - V_{th}$) and saturation ($V_{ds} \geq V_{gs} - V_{th}$) (Lurch, op. cit., p. 111). In EL applications, the drive transistors are typically operated in the saturation region to reduce the effect of V_{ds} variation on current. However, in the linear region of operation, where

$$I_{ds} = K[2(V_{gs} - V_{th})V_{ds} - V_{ds}^2]$$

(Lurch, op. cit., pg. 112), the current I_{ds} depends strongly on V_{ds} . Since

$$V_{ds} = (PVDD - V_{com}) - V_{oled}$$

as shown in FIG. 9, I_{ds} in the linear region depends strongly on V_{oled} . Therefore, taking current measurements in the linear region of operation of drive transistor 201 advantageously increases the magnitude of change in measured current between a new OLED emitter (511) and an aged OLED emitter (512a) compared to taking the same measurement in the saturation region.

[0062] One embodiment of the present invention, therefore, includes a voltage controller. While measuring currents as described above, the voltage controller can control voltages for the first voltage supply 211 and second voltage supply 206, and the drive transistor control signal from source driver 14 operating as a test voltage source, to operate drive transistor 201 in the linear region. For example, in a PMOS non-inverted configuration, the voltage controller can hold the PVDD voltage and the drive transistor control signal at constant values and increase the Vcom voltage to reduce V_{ds} without reducing V_{gs} . When V_{ds} falls below $V_{gs} - V_{th}$, the drive transistor will be operating in the linear region and a measurement can be taken. The voltage controller can be included in the compensator. It can also be provided separately from the sequence controller as long as the two are coordinated to operate the transistors in the linear region during measurements.

[0063] OLED efficiency loss is the tertiary aging effect. As an OLED ages, its efficiency decreases, and the same amount of current no longer produces the same amount of light. To compensate for this without requiring optical sensors or additional electronics, OLED efficiency loss as a function of V_{th} shift can be characterized, permitting estimation of the amount of extra current required to return the light output to its previous level. OLED efficiency loss can be characterized by driving an instrumented OLED subpixel with a typical input signal for a long period of time, and periodically measuring V_{th} , V_{oled} and I_{ds} at various drive levels. Efficiency can be calculated as I_{ds} / V_{oled} , and that calculation can be correlated to V_{th} or percent current. Note that this characterization achieves most effective results when V_{th} shift is always forward, since V_{th} shift is readily reversible but OLED efficiency loss is not. If V_{th} shift is reversed, correlating OLED efficiency loss with V_{th} shift can become complicated. For further processing, percent efficiency can be calculated as aged efficiency divided by new efficiency, analogously to the calculation of percent current described above.

[0064] Referring to FIG. 8, there is shown an experimental plot of percent efficiency as a function of percent current at various drive levels, with linear fits e.g. 90 to the experimental data. As the plot shows, at any given drive level, efficiency is linearly related to percent current. This linear model permits effective open-loop efficiency compensation.

[0065] To compensate for V_{th} and V_{oled} shift and OLED efficiency loss due to operation of the drive transistor and EL emitter over time, the second above embodiment of the status signal generation unit 240 can be used. Subpixel currents

can be measured at the measurement reference gate voltage 510. Unaged current at point 511 is target signal i_0 611. The most recent aged-subpixel current measurement 512a is most recent current measurement i_1 612. Percent current 613 is the status signal. Percent current 613 can be 0 (dead pixel), 1 (no change), less than 1 (current loss) or greater than 1 (current gain). Generally it will be between 0 and 1, because the most recent current measurement will be lower than the target signal, which can preferably be a current measurement taken at panel manufacturing time.

Implementation

[0066] Referring to FIG. 5A, there is shown an embodiment of a compensator 13. The input to compensator 13 is a linear code value 602, which can represent a commanded drive voltage for the EL subpixel 15. The compensator 13 changes the linear code value to produce a changed linear code value for a source driver, which can be e.g. a compensated voltage out 603. The compensator 13 can include four major blocks: determining a subpixel's age 61, optionally compensating for OLED efficiency 62, determining the compensation based on age 63, and compensating 64. Blocks 61 and 62 are primarily related to OLED efficiency compensation, and blocks 63 and 64 are primarily related to voltage compensation, specifically V_{th}/V_{oled} compensation.

[0067] FIG. 5B is an expanded view of blocks 61 and 62. As described above, the stored target signal i_0 611 and a stored most recent current measurement i_1 612 are retrieved, and percent current 613, the status signal for the subpixel, calculated.

[0068] Percent current 613 is sent to the next processing stage 63, and is also input to a model 695 to determine the percent OLED efficiency 614. Model 695 outputs an efficiency 614 which is the amount of light emitted for a given current at the time of the most recent measurement, divided by the amount of light emitted for that current at manufacturing time. Any percent current greater than 1 can yield an efficiency of 1, or no loss, since efficiency loss can be difficult to calculate for pixels which have gained current. Model 695 can also be a function of the linear code value 602, as indicated by the dashed arrow, in cases where OLED efficiency depends on commanded current. Whether to include linear code value 602 as an input to model 695 can be determined by life testing and modeling of a panel design.

[0069] Referring to FIG. 11, inventors have found that efficiency is generally a function of current density as well as of age. Each curve in FIG. 11 shows the relationship between current density, I_{ds} divided by emitter area, and efficiency (L_{oled}/I_{ds}) for an OLED aged to a particular point. The ages are indicated in the legend using the T notation known in the art: e.g. T86 means 86% efficiency at a test current density of e.g. 20 mA/cm².

[0070] Referring back to FIG. 5B, model 695 can therefore include an exponential term (or some other implementation) to compensate for current density and age. Current density is linearly related to linear code value 602, which represents a commanded voltage. Therefore, the compensator 13, of which model 695 is part, can change the linear code value in response to both the status signal (613) and the linear code value (602) to compensate for the variations in the characteristics of the drive transistor and EL emitter in the EL subpixel, and specifically for variations in the efficiency of the EL emitter in the EL subpixel.

[0071] In parallel, the compensator receives a linear code value 602, e.g. a commanded voltage. This linear code value 602 is passed through the original I-V curve 691 of the panel measured at manufacturing time to determine the desired current 621. This is divided by the percent efficiency 614 in operation 628 to return the light output for the desired current to its manufacturing-time value. The resulting, boosted current is then passed through curve 692, the inverse of curve 691, to determine what commanded voltage will produce the amount of light desired in the presence of efficiency loss. The value out of curve 692 is passed to the next stage as efficiency-adjusted voltage 622.

[0072] If efficiency compensation is not desired, linear code value 602 is sent unchanged to the next stage as efficiency-adjusted voltage 622, as indicated by optional bypass path 626. Percent current 613 is calculated whether or not efficiency compensation is desired, but the percent efficiency 614 need not be.

[0073] FIG. 5C is an expanded view of FIG. 5A, blocks 63 and 64. It receives a percent current 613 and an efficiency-adjusted voltage 622 from the previous stages. Block 63, "Get compensation," includes mapping the percent current 613 through the inverse I-V curve 692 and subtracting the result (FIG. 4A 513) from the measurement reference gate voltage (510) to find the V_{th} shift ΔV_{th} 631. Block 64, "Compensate," includes operation 633, which calculates the compensated voltage out 603 as given in Eq. 1:

$$V_{out} = V_{in} + \Delta V_{th} (1 + \alpha (V_{g,ref} - V_{in})) \quad (\text{Eq. 1})$$

where V_{out} is compensated voltage out 603, ΔV_{th} is voltage shift 631, α is alpha value 632, $V_{g,ref}$ is the measurement reference gate voltage 510, and V_{in} is the efficiency-adjusted voltage 622. The compensated voltage out can be expressed as a changed linear code value for a source driver, and compensates for variations in the characteristics of the drive transistor and EL emitter caused by operation of the drive transistor and EL emitter over time.

[0074] For straight V_{th} shift, α will be zero, and operation 633 will reduce to adding the V_{th} shift amount to the efficiency-adjusted voltage 622. For any particular subpixel, the amount to add is constant until new measurements are taken. When this is so, the voltage to add in operation 633 can be pre-computed after measurements are taken, permitting blocks 63 and 64 to collapse to looking up the stored value and adding it. This can save considerable logic.

Cross-domain processing, and bit depth

[0075] Image-processing paths known in the art typically produce nonlinear code values (NLCVs), that is, digital values having a nonlinear relationship to luminance (Giorgianni & Madden. Digital Color Management: encoding solutions. Reading, Mass.: Addison-Wesley, 1998. Ch. 13, pp. 283-295). Using nonlinear outputs matches the input domain of a typical source driver, and matches the code value precision range to the human eye's precision range. However, V_{th} shift is a voltage-domain operation, and thus is preferably implemented in a linear-voltage space. A source driver can be used, and domain conversion performed before the source driver, to effectively integrate a nonlinear-domain image-processing path with a linear-domain compensator. Note that this discussion is in terms of digital processing, but analogous processing can be performed in an analog or mixed digital/analog system. Note also that the compensator can operate in linear spaces other than voltage. For example, the compensator can operate in a linear current space.

[0076] Referring to FIG. 6, there is shown a Jones-diagram representation of the effect of a domain-conversion unit 12 in Quadrant I 127 and a compensator 13 in Quadrant II 137. This figure shows the mathematical effect of these units, not how they are implemented. The implementation of these units can be analog or digital, and can include a look-up table or function. Quadrant I represents the operation of the domain-conversion unit 12: nonlinear input signals, which can be nonlinear code values (NLCVs), on an axis 701 are converted by mapping them through a transform 711 to form linear code values (LCVs) on an axis 702. Quadrant II represents the operation of compensator 13: LCVs on axis 702 are mapped through transforms such as 721 and 722 to form changed linear code values (CLCVs) on axis 703.

[0077] Referring to Quadrant I, domain-conversion unit 12 receives respective NLCVs for each subpixel, and converts them to LCVs. This conversion should be performed with sufficient resolution to avoid objectionable visible artifacts such as contouring and crushed blacks. In digital systems, NLCV axis 701 can be quantized, as indicated in FIG. 6. For quantized NLCVs, LCV axis 702 should have sufficient resolution to represent the smallest change in transform 711 between two adjacent NLCVs. This is shown as NLCV step 712 and corresponding LCV step 713. As the LCVs are by definition linear, the resolution of the whole LCV axis 702 should be sufficient to represent step 713. Consequently, the LCVs can be defined with finer resolution than the NLCVs in order to avoid loss of image information. The resolution can be twice that of step 713 by analogy with the Nyquist sampling theorem.

[0078] Transform 711 is an ideal transform for an unaged subpixel. It has no relationship to aging of any subpixel or the panel as a whole. Specifically, transform 711 is not modified due to any V_{th} , V_{oled} , or OLED efficiency changes. There can be one transform for all colors, or one transform for each color. The domain-conversion unit, through transform 711, advantageously decouples the image-processing path from the compensator, permitting the two to operate together without having to share information. This simplifies the implementation of both. Domain-conversion unit 12 can be implemented as a look-up table or a function analogous to an LCD source driver.

[0079] Referring to Quadrant II, compensator 13 changes LCVs to changed linear code values (CLCVs). FIG. 6 shows the simple case, correction for straight V_{th} shift, without loss of generality. Straight V_{th} shift can be corrected for by straight voltage shift from LCVs to CLCVs. Other aging effects can be handled as described above in "Implementation."

[0080] Transform 721 represents the compensator's behavior for an unaged subpixel, for which the CLCV can be the same as the LCV. Transform 722 represents the compensator's behavior for an aged subpixel, for which the CLCV can be the LCV plus an offset representing the V_{th} shift of the subpixel in question. Consequently, the CLCVs will generally require a large range than the LCVs in order to provide headroom for compensation. For example, if a subpixel requires 256 LCVs when it is new, and the maximum shift over its lifetime is 128 LCVs, the CLCVs will need to be able to represent values up to $384 = 256 + 128$ to avoid clipping the compensation of heavily-aged subpixels.

[0081] FIG. 6 shows a complete example of the effect of the domain-conversion unit and compensator. Following the dash-dot arrows in FIG. 6, an NLCV of 3 is transformed by the domain-conversion unit 12 through transform 711 to an LCV of 9, as indicated in Quadrant I. For an unaged subpixel, the compensator 13 will pass that through transform 721 as a CLCV of 9, as indicated in Quadrant II. For an aged subpixel with a V_{th} shift analogous to 12 CLCVs, the LCV of 9 will be converted through transform 722 to a CLCV of $9 + 12 = 21$.

[0082] In one embodiment, the NLCVs from the image-processing path are nine bits wide. The LCVs are 11 bits wide. The transformation from nonlinear input signals to linear code values can be performed by a LUT or function. The compensator can take in the 11-bit linear code value representing the desired voltage and produce a 12-bit changed linear code value to send to a source driver 14. The source driver 14 can then drive the gate electrode of the drive transistor of the EL subpixel in response to the changed linear code value. The compensator can have greater bit depth on its output than its input to provide headroom for compensation, that is, to extend the voltage range 78 to voltage range 79 and simultaneously keep the same resolution across the new, expanded range, as required for minimum linear

code value step 713. The compensator output range can extend below the range of transform 721 as well as above it.

[0083] Each panel design can be characterized to determine what the maximum V_{th} shift, V_{oled} rise and efficiency loss will be over the design life of a panel, and the compensator and source drivers can have enough range to compensate. This characterization can proceed from required current to required gate bias and transistor dimensions via the standard transistor saturation-region I_{ds} equation, then to V_{th} shift over time via various models known in the art for a-Si degradation over time.

Sequence of operations

Panel design characterization

[0084] This section is written in the context of mass-production of a particular OLED emitter design. Before mass-production begins, the design can be characterized: accelerated life testing can be performed, and I-V curves can be measured for various subpixels of various colors on various sample substrates aged to various levels. The number and type of measurements required, and of aging levels, depend on the characteristics of the particular panel. With these measurements, a value alpha (α) can be calculated and a measurement reference gate voltage can be selected. Alpha (FIG. 5C, item 632) is a value representing the deviation from a straight shift over time. An α value of 0 indicates all aging is a straight shift on the voltage axis, as would be the case e.g. for V_{th} shift alone. The measurement reference gate voltage (FIG. 4A 510) is the voltage at which aging signal measurements are taken for compensation, and can be selected to provide acceptable S/N ratio and keep power dissipation low.

[0085] The α value can be calculated by optimization. An example is given in Table 1. ΔV_{th} can be measured at a number of gate voltages, under a number of aging conditions. ΔV_{th} differences are then calculated between each ΔV_{th} and the ΔV_{th} at the measurement reference gate voltage 510. V_g differences are calculated between each gate voltage and the measurement reference gate voltage 510. The inner term of Eq. 1, $\Delta V_{th} \cdot \alpha \cdot (V_{g,ref} - V_{in})$, can then be computed for each measurement to yield a predicted ΔV_{th} difference, using the appropriate ΔV_{th} at the measurement reference gate voltage 510 as ΔV_{th} in the equation, and using the appropriate calculated gate voltage difference as $(V_{g,ref} - V_{in})$. The α value can then be selected iteratively to reduce, and preferably mathematically minimize, the error between the predicted ΔV_{th} differences and the calculated ΔV_{th} differences. Error can be expressed as the maximum difference or the RMS difference. Alternative methods known in the art, such as least-squares fitting of ΔV_{th} difference as a function of V_g difference, can also be used.

Table 1: Example of α calculation

Vg	ΔV_{th}		V_g difference	ΔV_{th} difference		Predicted ΔV_{th} difference		Error	
	Day 1	Day 8		Day 1	Day 8	Day 1	Day 8	Day 1	Day 8
ref = 13.35	0.96	2.07	0	0	0	0.00	0.00	0.00	0.00
12.54	1.05	2.17	0.81	0.09	0.1	0.04	0.08	0.05	0.02
11.72	1.1	2.23	1.63	0.14	0.16	0.08	0.17	0.06	-0.01
10.06	1.2	2.32	3.29	0.24	0.25	0.16	0.33	0.08	-0.08
$V_{g,ref} - V_{in}$						$\alpha = 0.0491$		max = 0.08	

[0086] In addition to α and the measurement reference gate voltage, characterization can also determine, as described above, V_{oled} shift as a function of V_{th} shift, efficiency loss as a function of V_{th} shift, self-heating component per subpixel, maximum V_{th} shift, V_{oled} shift and efficiency loss, and resolution required in the nonlinear-to-linear transform and in the compensator. Resolution required can be characterized in conjunction with a panel calibration procedure such as co-pending commonly-assigned U.S. Patent Application Publication No. 2008/0252653, the disclosure of which is incorporated herein. Characterization also determines, as will be described in "In the field," below, the conditions for taking characterization measurements in the field, and which embodiment of the status signal generation unit 240 to employ for a particular panel design. All these determinations can be made by those skilled in the art.

Mass-production

[0087] Once the design has been characterized, mass-production can begin. At manufacturing time, appropriate values are measured for each subpixel produced according to a selected embodiment of the status signal generation unit 240. For example, I-V curves and subpixel currents can be measured. Current can be measured at enough drive voltages to make a realistic I-V curve; any errors in the I-V curve can affect the results. Subpixel currents can be measured at the

measurement reference gate voltage to provide target signals i_0 611. The I-V curves and reference currents are stored in a nonvolatile memory associated with the subpixel and it is sent into the field.

In the field

[0088] Once in the field, the subpixel ages at a rate determined by on how hard it is driven. After some time the subpixel has shifted far enough that it needs to be compensated; how to determine that time is considered below.

[0089] To compensate, compensation measurements are taken and applied. The compensation measurements are of the current of the subpixel at the measurement reference gate voltage. The measurements are applied as described in "Algorithm," above. The measurements are stored so they can be applied whenever that subpixel is driven, until the next time measurements are taken.

[0090] Compensation measurements can be taken as frequently or infrequently as desired; a typical range can be once every eight hours to once every four weeks. FIG. 7 shows one example of how often compensation measurements might have to be taken as a function of how long the panel is active. This curve is only an example; in practice, this curve can be determined for any particular subpixel design through accelerated life testing of that design. The measurement frequency can be selected based on the rate of change in the characteristics of the drive transistor and EL emitter over time; both shift faster when the panel is new, so compensation measurements can be taken more frequently when the panel is new than when it is old. There are a number of ways to determine when to take compensation measurements. For example, the current drawn by the subpixel at some given drive voltage can be measured and compared to a previous result of the same measurement. In another example, environmental factors which affect the panel, such as temperature and ambient light, can be measured, and compensation measurements taken e.g. if the ambient temperature has changed more than some threshold.

[0091] For example, the EL subpixel 15 shown in FIG. 2 is for an N-channel drive transistor and a non-inverted EL structure. The EL emitter 202 is tied to the second supply electrode 205, which is the source of the drive transistor 201, higher voltages on the gate electrode 203 command more light output, and voltage supply 211 is more positive than second voltage supply 206, so current flows from 211 to 206. However, this invention is applicable to any combination of P- or N-channel drive transistors and non-inverted (common-cathode) or inverted (common-anode) EL emitters. The appropriate modifications to the circuits for these cases are well-known in the art.

[0092] In a preferred embodiment, the invention is employed in a subpixel that includes Organic Light Emitting Diodes (OLEDs) which are composed of small molecule or polymeric OLEDs as disclosed in but not limited to U.S. Patent No. 4,769,292, by Tang et al., and U.S. Patent No. 5,061,569, by VanSlyke et al. Many combinations and variations of organic light emitting materials can be used to fabricate such a panel. Referring to FIG. 2, when EL emitter 202 is an OLED emitter, EL subpixel 15 is an OLED subpixel. This invention also applies to EL emitters other than OLEDs. Although the degradation modes of other EL emitter types can be different than the degradation modes described herein, the measurement, modeling, and compensation techniques of the present invention can still be applied.

[0093] The above embodiments can apply to any active matrix backplane that is not stable as a function of time (such as a-Si). For example, transistors formed from organic semiconductor materials and zinc oxide are known to vary as a function of time and therefore this same approach can be applied to these transistors. Furthermore, as the present invention can compensate for EL emitter aging independently of transistor aging, this invention can also be applied to an active-matrix backplane with transistors that do not age, such as low-temperature poly-silicon (LTPS) TFTs. On an LTPS backplane, the drive transistor 201 and select transistor 36 are low-temperature polysilicon transistors.

PARTS LIST

[0094]

- 10 system
- 11 nonlinear input signal
- 12 converter to voltage domain
- 13 compensator
- 14 source driver
- 15 EL subpixel
- 16 current-measurement circuit
- 32 column line
- 34 gate line
- 36 select transistor
- 41 measurement
- 43 difference

	49	measurement
	61	block
	62	block
	63	block
5	64	block
	78	voltage range
	79	voltage range
	90	linear fit
	127	quadrant
10	137	quadrant
	200	switch
	201	drive transistor
	202	EL emitter
	203	gate electrode
15	204	first supply electrode
	205	second supply electrode
	206	voltage supply
	207	first electrode
	208	second electrode
20	210	current mirror unit
	211	voltage supply
	212	first current mirror
	213	first current mirror output
	214	second current mirror
25	215	bias supply
	216	current-to-voltage converter
	220	correlated double-sampling unit
	221	sample-and-hold unit
	222	sample-and-hold unit
30	223	differential amplifier
	230	analog-to-digital converter
	240	status signal generation unit
	501	unaged I-V curve
	502	aged I-V curve
35	503	voltage difference
	504	voltage difference
	505	voltage difference
	506	voltage difference
	510	measurement reference gate voltage
40	511	current
	512a	current
	512b	current
	513	voltage
	514	voltage shift
45	550	voltage shift
	552	voltage shift
	602	linear code value
	603	compensated voltage
	611	current
50	612	current
	613	percent current
	614	percent efficiency
	615	mura-correction gain term
	616	mura-correction offset term
55	619	memory
	621	current
	622	voltage
	626	block

628 operation
 631 voltage shift
 632 alpha value
 633 operation
 5 691 I-V curve
 692 inverse of I-V curve
 695 model
 701 axis
 702 axis
 10 703 axis
 711 smallest change in transform
 712 step
 713 step
 721 transform
 15 722 transform
 1002 storage capacitor
 1011 bus line
 1012 sheet cathode

20

Claims

1. Apparatus for providing a drive transistor control signal to a gate electrode (203) of a drive transistor (201) in an electroluminescent, EL, subpixel (15), comprising:
 25
 (a) the electroluminescent, EL, subpixel (15) having an EL emitter (202) with a first and second electrode (207, 208), and having the drive transistor (201) with a first supply electrode (204), a second supply electrode (205), and the gate electrode (203), wherein the second supply electrode (205) of the drive transistor (201) is electrically connected to the first electrode (207) of the EL emitter (202) for applying current to the EL emitter (202);
 30
 (b) a first voltage supply (211) electrically connected to the first supply electrode (204) of the drive transistor (201);
 (c) a second voltage supply (206) electrically connected to the second electrode (208) of the EL emitter (202);
 (d) a test voltage source (14) electrically connected to the gate electrode (203) of the drive transistor (201);
 (e) a voltage controller for controlling voltages of the first voltage supply (211), second voltage supply (206) and test voltage source (14) to operate the drive transistor (201) in a linear region;
 35
 (f) a measuring circuit (16) for measuring the current passing through the first and second supply electrodes (204, 205) of the drive transistor (201) at different times to provide a status signal representing variations in the characteristics of the drive transistor (201) and EL (202) emitter caused by operation of the drive transistor (201) and EL emitter (202) over time, wherein the current is measured while the drive transistor (201) is operated in the linear region;
 40
 (g) means for providing a linear code value (12);
 (h) a compensator (13) for changing the linear code value in response to the status signal to compensate for the variations in the characteristics of the drive transistor (201) and EL emitter (202); and
 (i) a source driver (14) for producing the drive transistor control signal in response to the changed linear code value for driving the gate electrode (203) of the drive transistor (201),
 45
 characterized in that
 the measuring circuit (16) includes a first current mirror (212) for producing a mirrored current which is a function of the drive current passing through the first and second supply electrodes (204, 205) and a second current mirror (214) for applying a bias current to the first current mirror to reduce impedance of the first current mirror.
 50
 2. The apparatus of claim 1, wherein the EL emitter (202) is an OLED emitter.
 3. The apparatus of claim 1, wherein the drive transistor (201) is a low temperature polysilicon transistor.
 55 4. The apparatus of claim 1, further including a switch for selectively electrically connecting the measuring circuit (16) to the current flow through the first and second supply electrodes (204, 205).
 5. The apparatus of claim 1, wherein the measuring circuit (16) further includes a current to voltage converter (216)

responsive to the mirrored current for producing a voltage signal and means (240) responsive to the voltage signal for providing the status signal to the compensator (13).

6. The apparatus of claim 1, wherein the drive transistor control signal is a voltage.

7. The apparatus of claim 1, wherein the measuring circuit (16) further includes a memory (220) for storing a target signal and a most recent current measurement.

Patentansprüche

1. Vorrichtung zum Bereitstellen eines Ansteuertransistor-Steuersignals an eine Gate-Elektrode (203) eines Ansteuertransistors (201) in einem Elektrolumineszenz, EL,-Subpixel (15), umfassend:

(a) das Elektrolumineszenz, EL,-Subpixel (15), das einen EL-Emitter (202) mit einer ersten und einer zweiten Elektrode (207, 208) aufweist und das den Ansteuertransistor (201) mit einer ersten Versorgungselektrode (204), eine zweite Versorgungselektrode (205) und die Gate-Elektrode (203) aufweist, wobei die zweite Versorgungselektrode (205) des Ansteuertransistors (201) elektrisch mit der ersten Elektrode (207) des EL-Emitters (202) zum Anlegen von Strom an den EL-Emitter (202) verbunden ist;

(b) eine erste Spannungsversorgung (211), die elektrisch mit der ersten Versorgungselektrode (204) des Ansteuertransistors (201) verbunden ist;

(c) eine zweite Spannungsversorgung (206), die elektrisch mit der zweiten Elektrode (208) des EL-Emitters (202) verbunden ist;

(d) eine Prüfspannungsquelle (14), die elektrisch mit der Gate-Elektrode (203) des Ansteuertransistors (201) verbunden ist;

(e) eine Spannungssteuerung zum Steuern von Spannungen der ersten Spannungsversorgung (211), der zweiten Spannungsversorgung (206) und der Prüfspannungsquelle (14), um den Ansteuertransistor (201) in einem linearen Bereich zu betreiben;

(f) eine Meßschaltung (16) zum Messen des Stroms, der zu unterschiedlichen Zeiten durch die erste und die zweite Versorgungselektrode (204, 205) des Ansteuertransistors (201) fließt, um ein Statussignal bereitzustellen, das Schwankungen bei den Merkmalen des Ansteuertransistors (201) und des EL (202)-Emitters darstellt, die durch den Betrieb des Ansteuertransistors (201) und des EL-Emitters (202) im Laufe der Zeit verursacht werden, wobei der Strom gemessen wird, während der Ansteuertransistor (201) im linearen Bereich betrieben wird;

(g) Mittel zum Bereitstellen eines linearen Codewertes (12);

(h) einen Kompensator (13) zum Verändern des linearen Codewertes in Reaktion auf das Statussignal, um die Schwankungen bei den Eigenschaften des Ansteuertransistors (201) und des EL-Emitters (202) zu kompensieren; und

(i) einen Sourcetreiber (14) zum Erzeugen des Ansteuertransistor-Steuersignals in Reaktion auf den veränderten linearen Codewert zum Ansteuern der Gate-Elektrode (203) des Ansteuertransistors (201),

dadurch gekennzeichnet, dass

die Messschaltung (16) einen ersten Stromspiegel (212) zum Erzeugen eines gespiegelten Stroms, der eine Funktion des Ansteuerstroms ist, der durch die erste und die zweite Versorgungselektrode (204, 205) fließt, und einen zweiten Stromspiegel (214) zum Anlegen eines Vorspannungsstroms an den ersten Stromspiegel zum Verringern einer Impedanz des ersten Stromspiegels beinhaltet.

2. Vorrichtung nach Anspruch 1, wobei der EL-Emitter (202) ein OLED-Emitter ist.

3. Vorrichtung nach Anspruch 1, wobei der Ansteuertransistor (201) ein Niedertemperatur-Polysilizium-Transistor ist.

4. Vorrichtung nach Anspruch 1, ferner beinhaltend einen Schalter, um die Messschaltung (16) selektiv mit dem Stromfluss durch die erste und die zweite Versorgungselektrode (204, 205) elektrisch zu verbinden.

5. Vorrichtung nach Anspruch 1, wobei die Messschaltung (16) ferner einen Strom-Spannungswandler (216) in Reaktion auf den gespiegelten Strom zum Erzeugen eines Spannungssignals und Mittel (240) in Reaktion auf das Spannungssignal zum Bereitstellen des Statussignals an den Kompensator (13) beinhaltet.

6. Vorrichtung nach Anspruch 1, wobei das Ansteuertransistor-Steuersignal eine Spannung ist.
7. Vorrichtung nach Anspruch 1, wobei die Messschaltung (16) ferner einen Speicher (220) zum Speichern eines Zielsignals und einer neuesten Spannungsmessung beinhaltet.

5

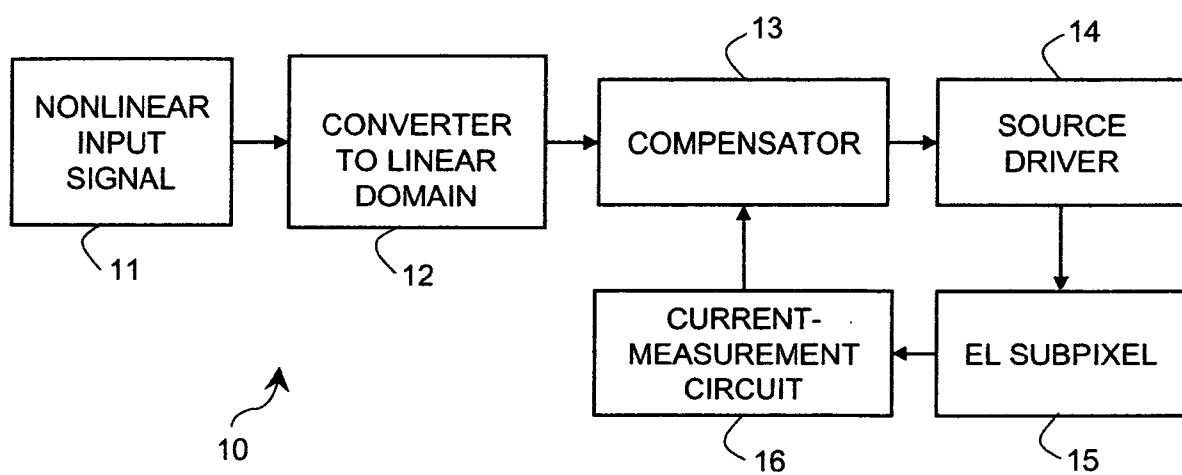
Revendications

1. Appareil pour fournir un signal de commande de transistor de pilotage à une électrode de grille (203) d'un transistor de pilotage (201) dans un sous-pixel électroluminescent, EL, (15), comprenant :
- (a) le sous-pixel électroluminescent, EL, (15) ayant un émetteur EL (202) avec une première et une seconde électrode (207, 208), et ayant le transistor de pilotage (201) avec une première électrode d'alimentation (204), une seconde électrode d'alimentation (205) et l'électrode de grille (203), la seconde électrode d'alimentation (205) du transistor de pilotage (201) étant connectée électriquement à la première électrode (207) de l'émetteur EL (202) pour appliquer un courant sur l'émetteur EL (202) ;
- (b) une première alimentation en tension (211) connectée électriquement à la première électrode d'alimentation (204) du transistor de pilotage (201) ;
- (c) une seconde alimentation en tension (206) connectée électriquement à la seconde électrode (208) de l'émetteur EL (202) ;
- (d) une source de tension d'essai (14) connectée électriquement à l'électrode de grille (203) du transistor de pilotage (201) ;
- (e) un dispositif de commande de tensions pour commander des tensions de la première alimentation en tension (211), de la seconde alimentation en tension (206) et de la source de tension d'essai (14) pour faire fonctionner le transistor de pilotage (201) dans une région linéaire ;
- (f) un circuit de mesure (16) pour mesurer le courant passant à travers les première et seconde électrodes d'alimentation (204, 205) du transistor de pilotage (201) à différents instants pour fournir un signal d'état représentant des variations des caractéristiques du transistor de pilotage (201) et de l'émetteur EL (202) provoquées par le fonctionnement du transistor de pilotage (201) et de l'émetteur EL (202) au cours du temps, le courant étant mesuré pendant que le transistor de pilotage (201) fonctionne dans la région linéaire ;
- (g) des moyens pour fournir une valeur de code linéaire (12) ;
- (h) un compensateur (13) pour modifier la valeur de code linéaire en réponse au signal d'état pour compenser les variations des caractéristiques du transistor de pilotage (201) et de l'émetteur EL (202) ; et
- (i) un dispositif de pilotage de source (14) pour produire le signal de commande de transistor de pilotage en réponse à la valeur de code linéaire modifiée pour piloter l'électrode de grille (203) du transistor de pilotage (201),

caractérisé par le fait que

le circuit de mesure (16) comprend un premier miroir de courant (212) pour produire un courant en miroir qui est une fonction du courant de pilotage passant à travers les première et seconde électrodes d'alimentation (204, 205) et un second miroir de courant (214) pour appliquer un courant de polarisation sur le premier miroir de courant pour réduire l'impédance du premier miroir de courant.

2. Appareil selon la revendication 1, dans lequel l'émetteur EL (202) est un émetteur OLED.
3. Appareil selon la revendication 1, dans lequel le transistor de pilotage (201) est un transistor en silicium polycristallin basse température.
4. Appareil selon la revendication 1, comprenant en outre un commutateur pour connecter électriquement sélectivement le circuit de mesure (16) au flux de courant à travers les première et seconde électrodes d'alimentation (204, 205).
5. Appareil selon la revendication 1, dans lequel le circuit de mesure (16) comprend en outre un convertisseur courant-tension (216) réactif au courant en miroir pour produire un signal de tension et des moyens (240) réactifs au signal de tension pour fournir le signal d'état au compensateur (13).
6. Appareil selon la revendication 1, dans lequel le signal de commande de transistor de pilotage est une tension.
7. Appareil selon la revendication 1, dans lequel le circuit de mesure (16) comprend en outre une mémoire (220) pour stocker un signal cible et une mesure de courant la plus récente.

**FIG. 1**

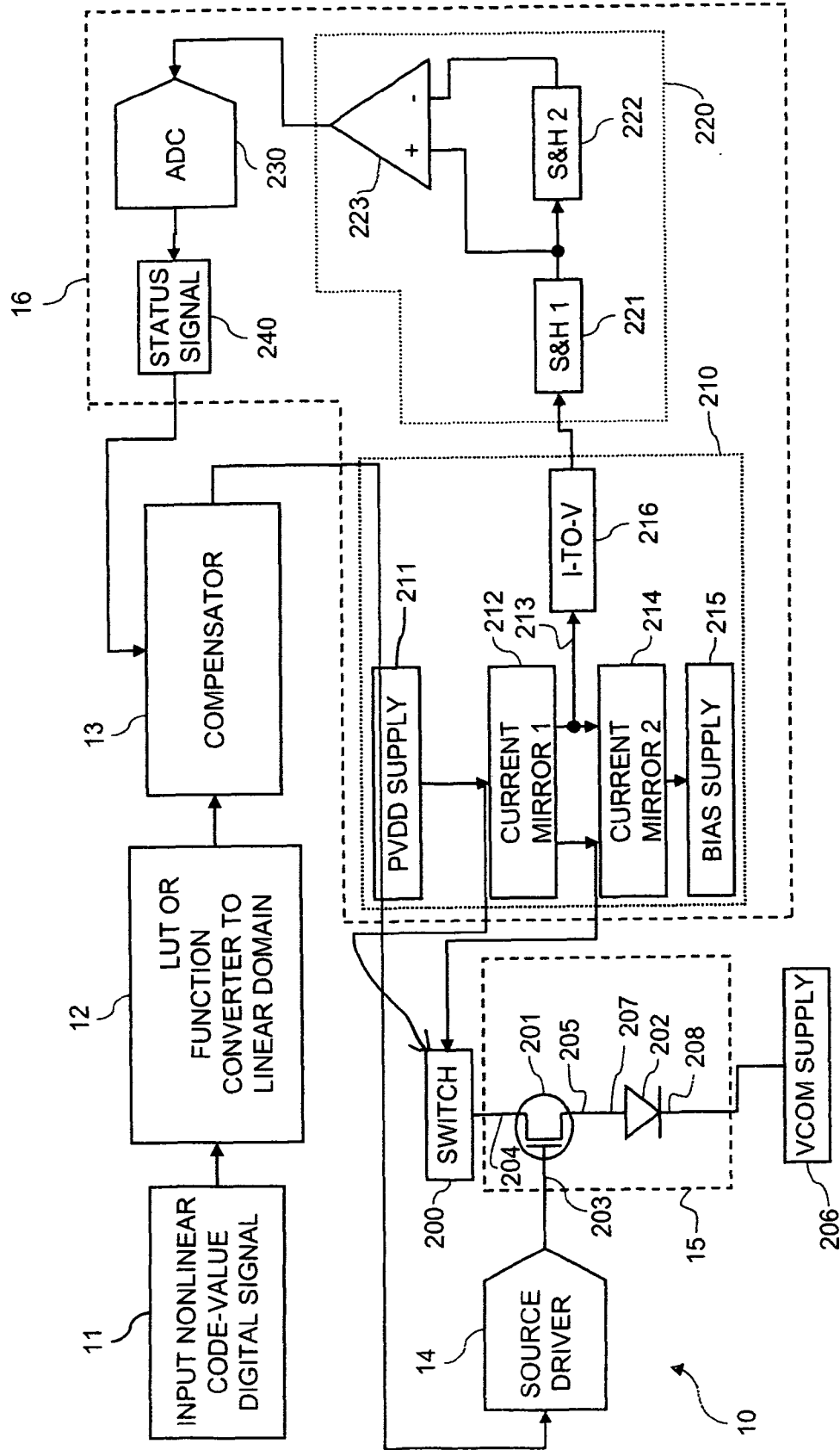


FIG. 2

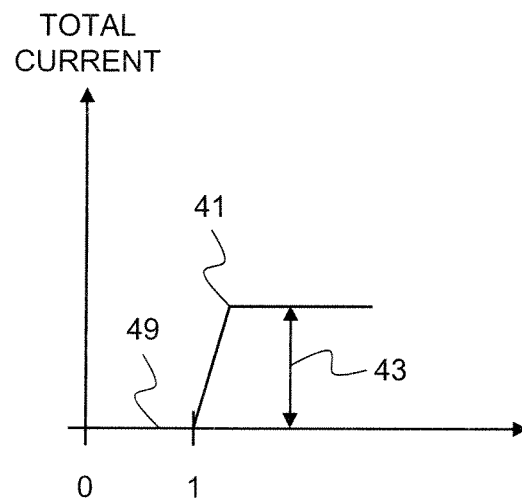


FIG. 3

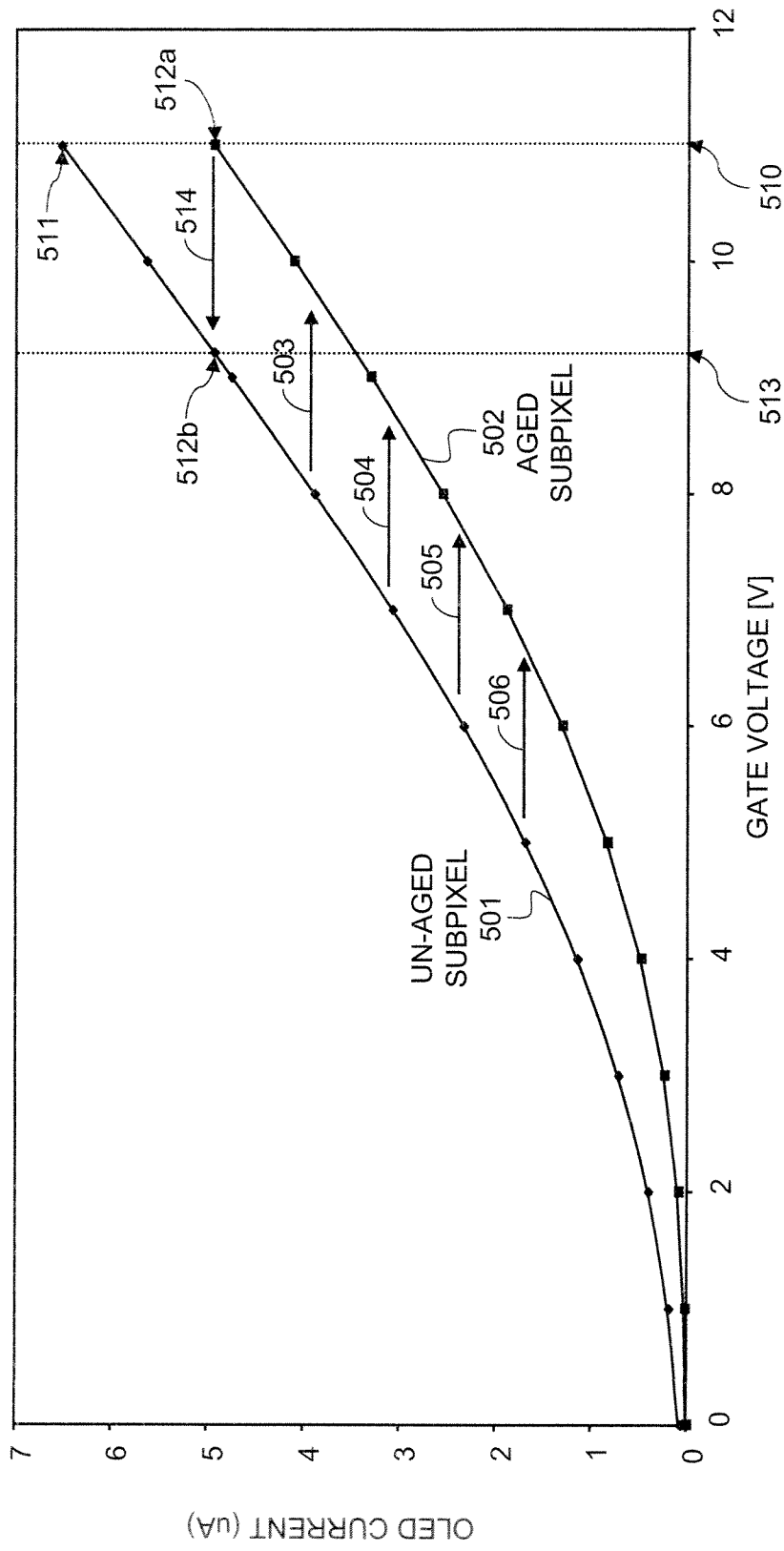


FIG. 4A

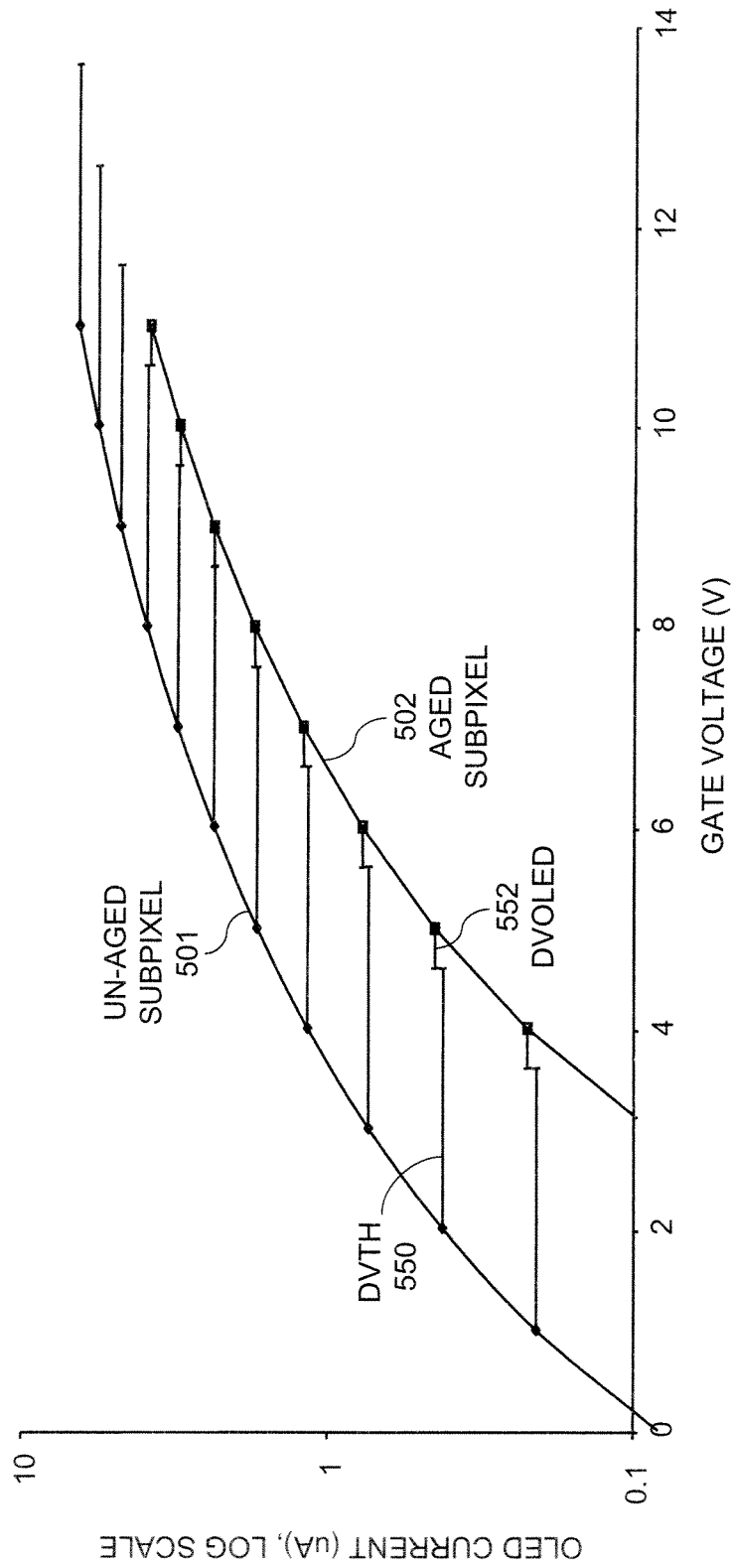
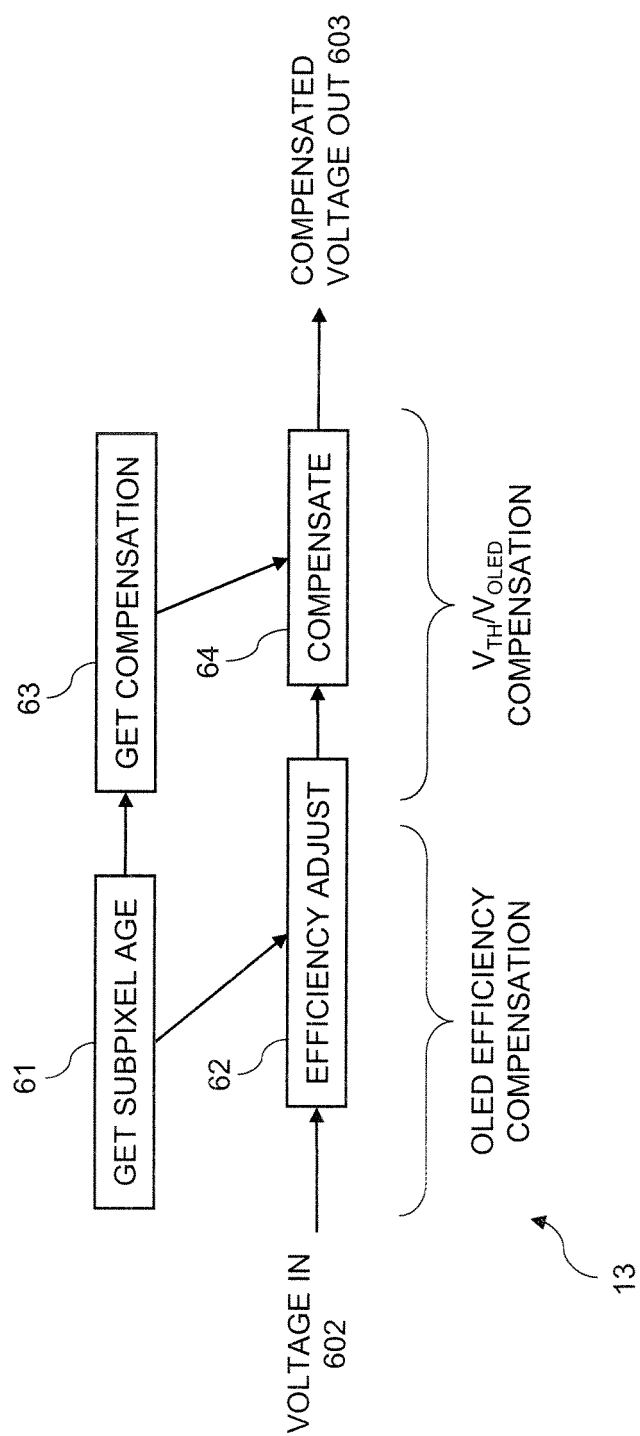


FIG. 4B

**FIG. 5A**

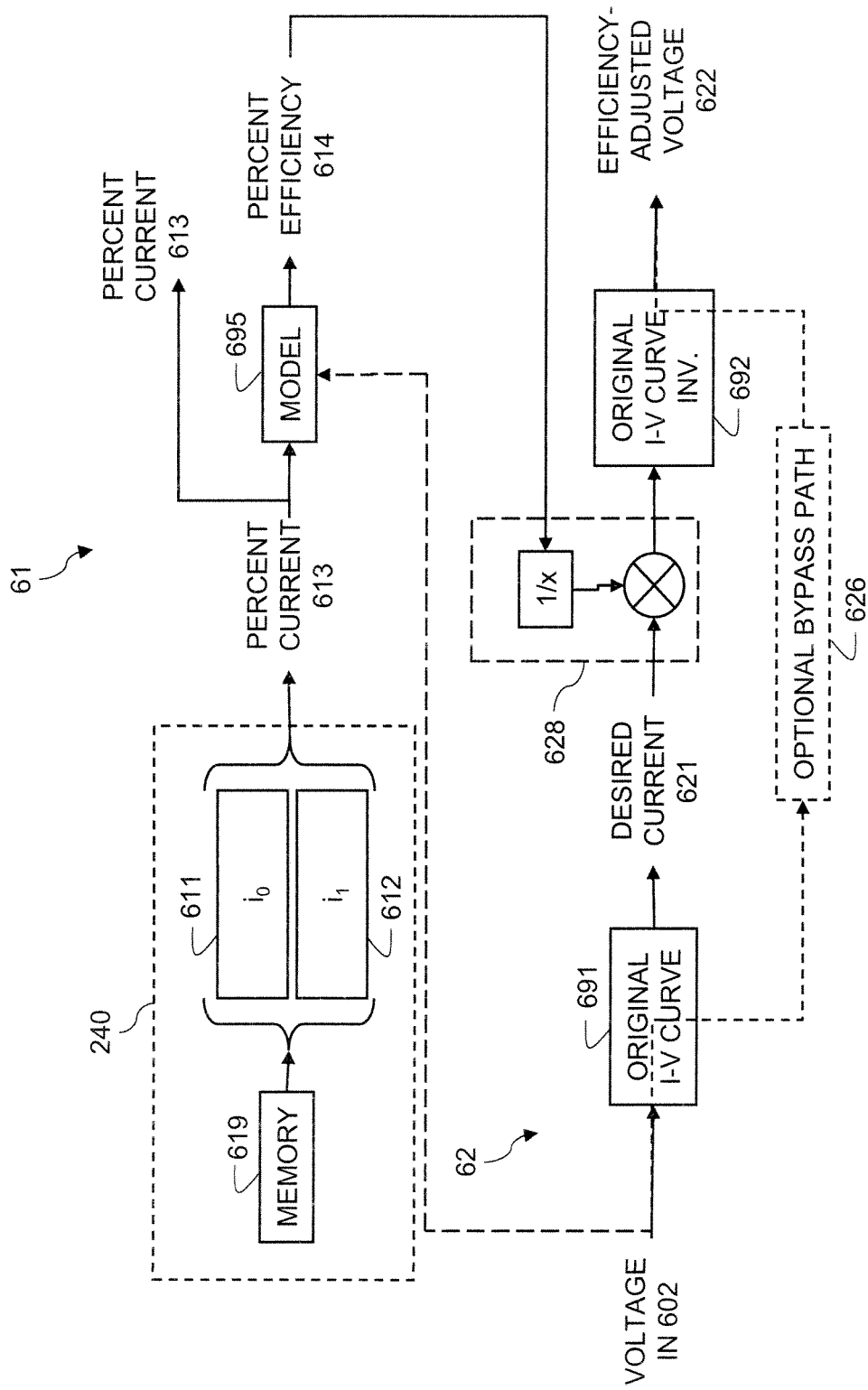


FIG. 5B

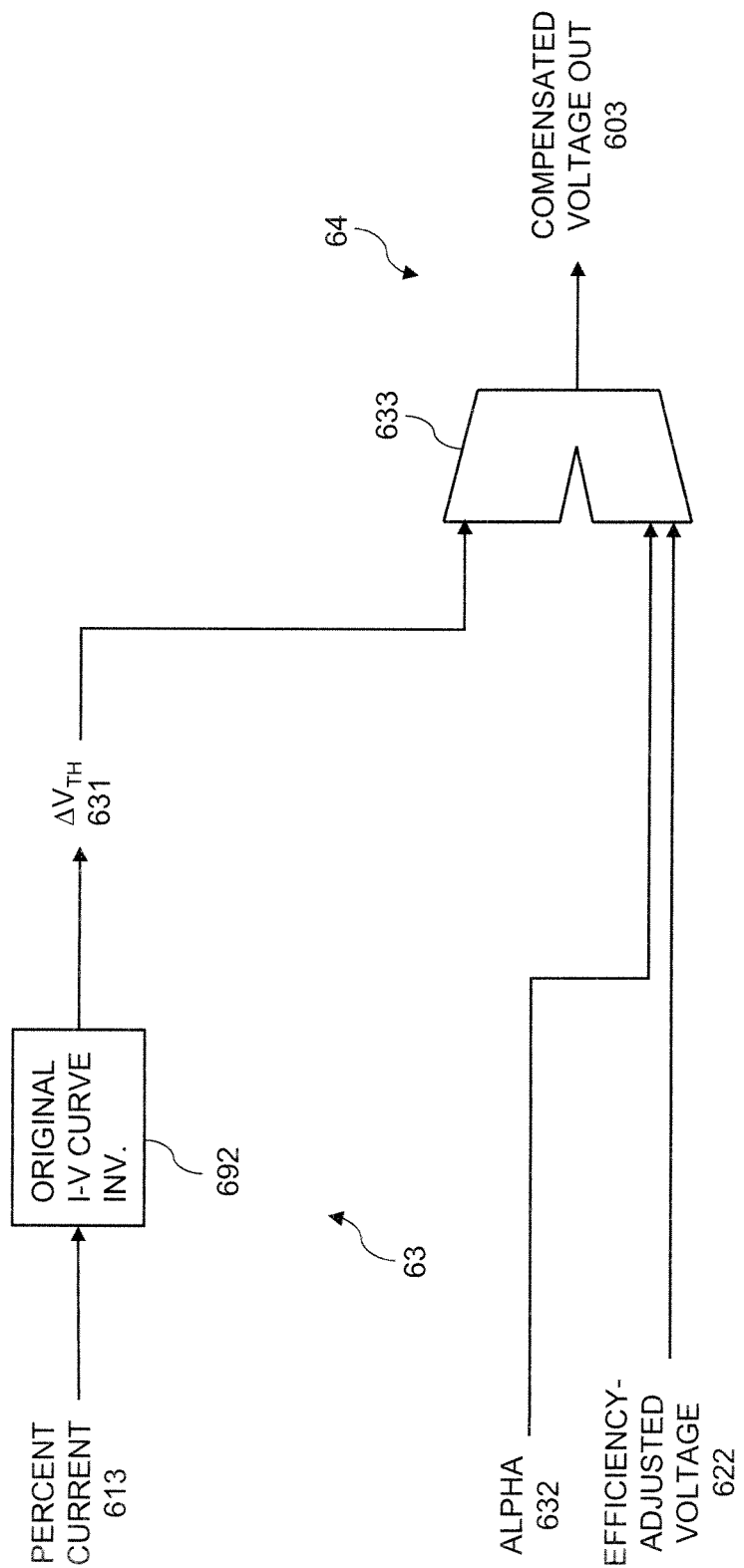


FIG. 5C

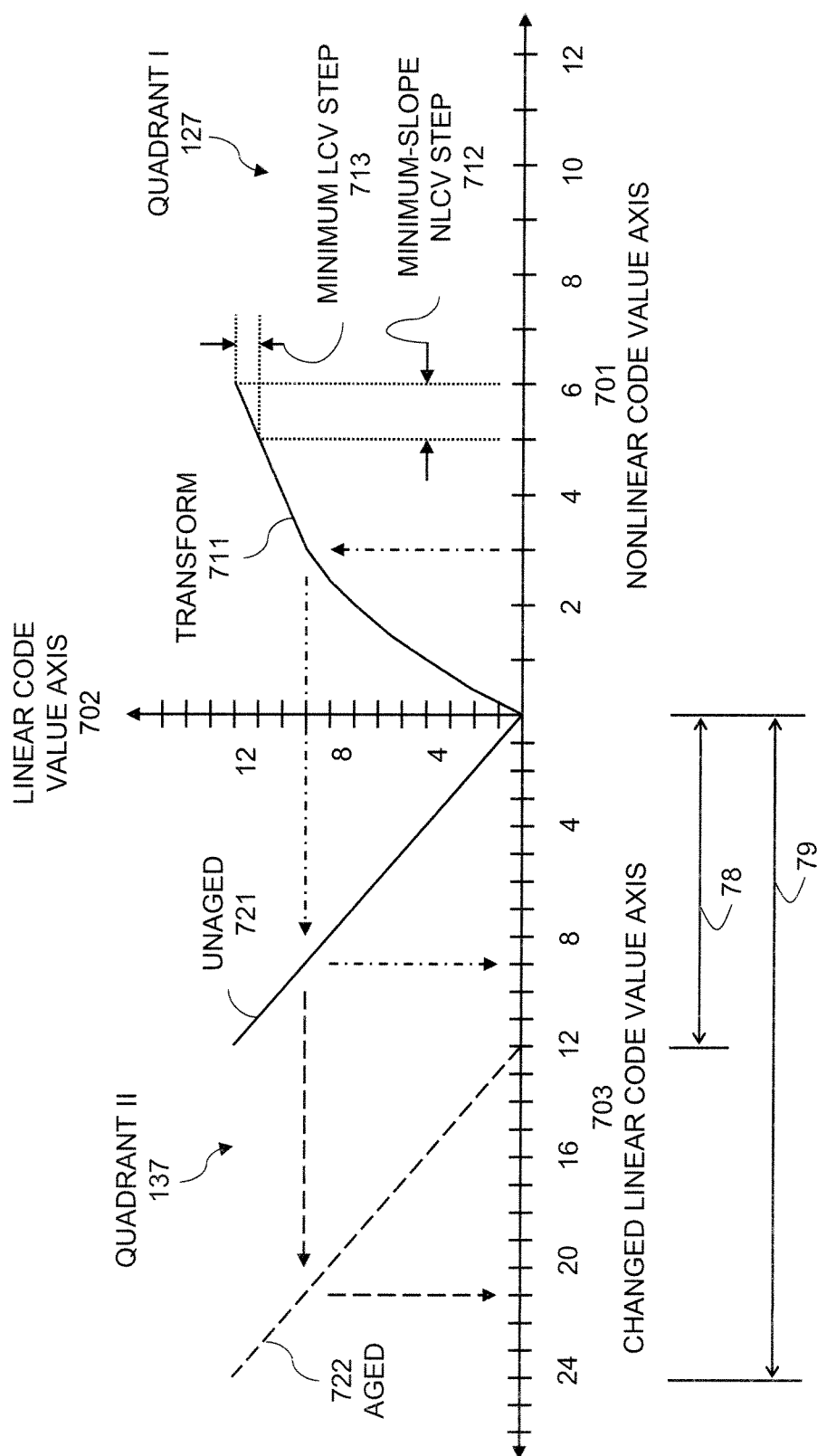


FIG. 6

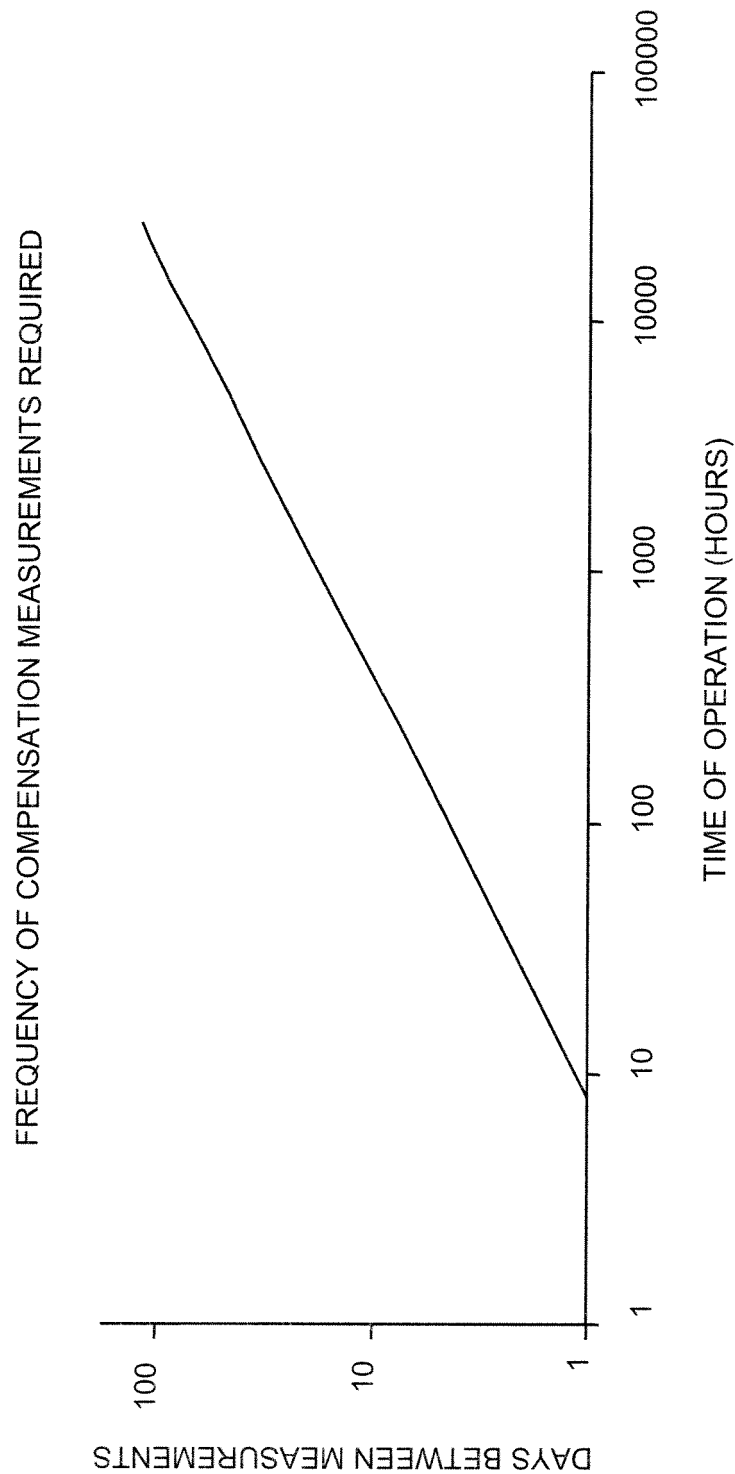


FIG. 7

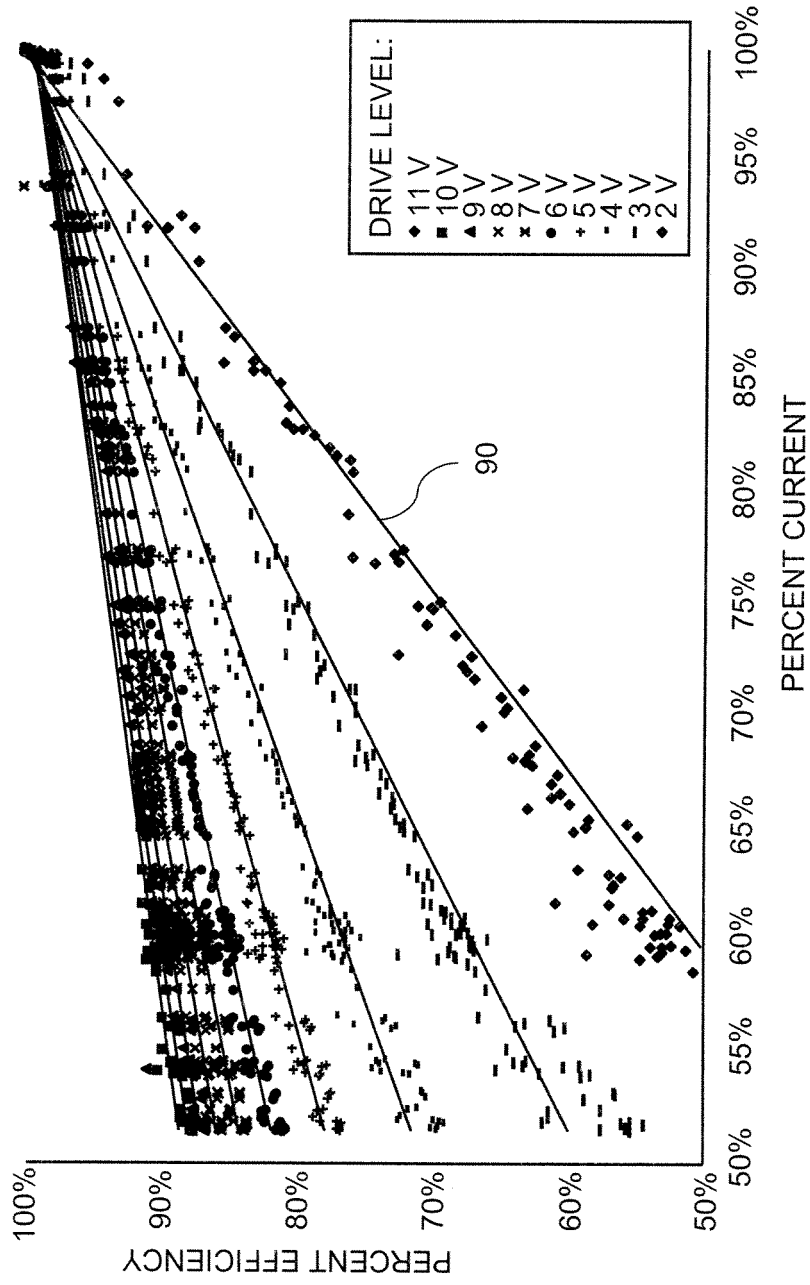


FIG. 8

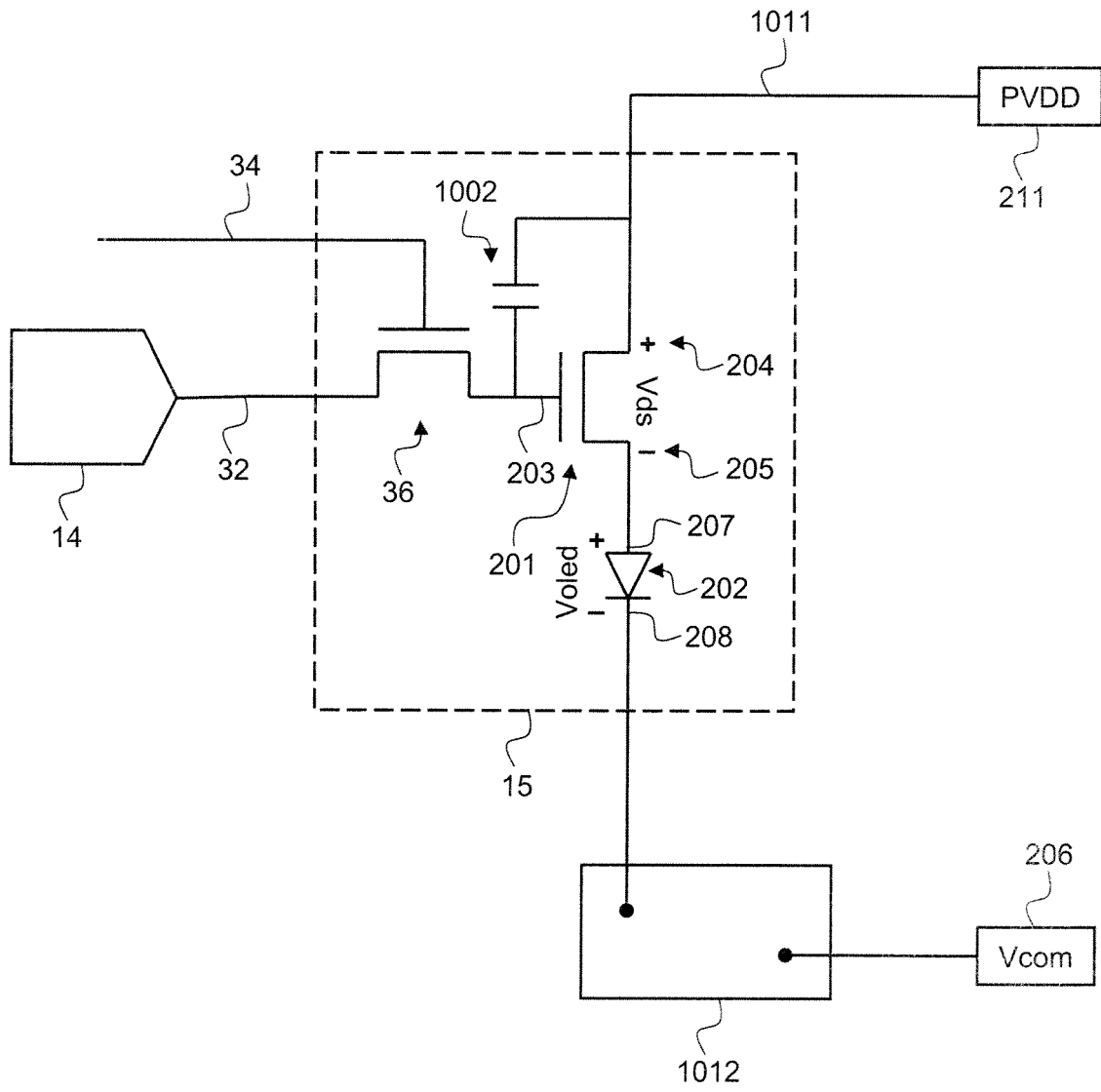


FIG. 9

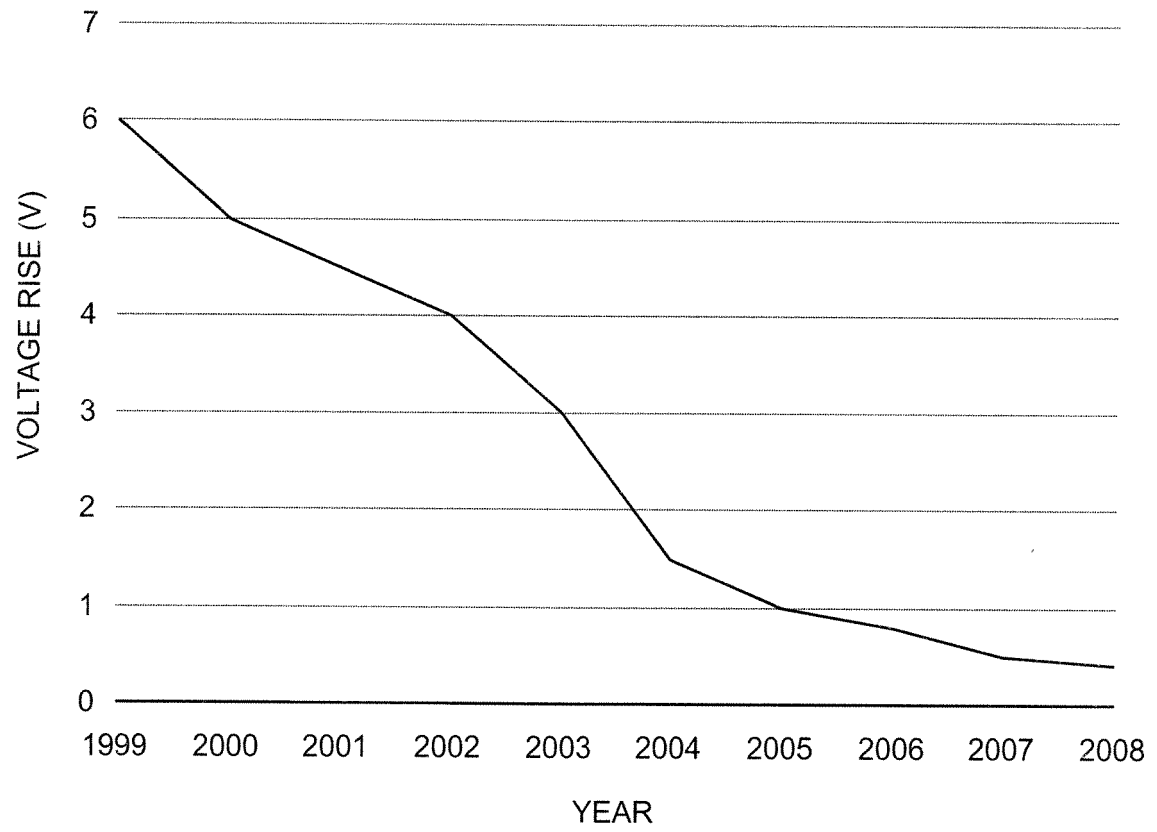
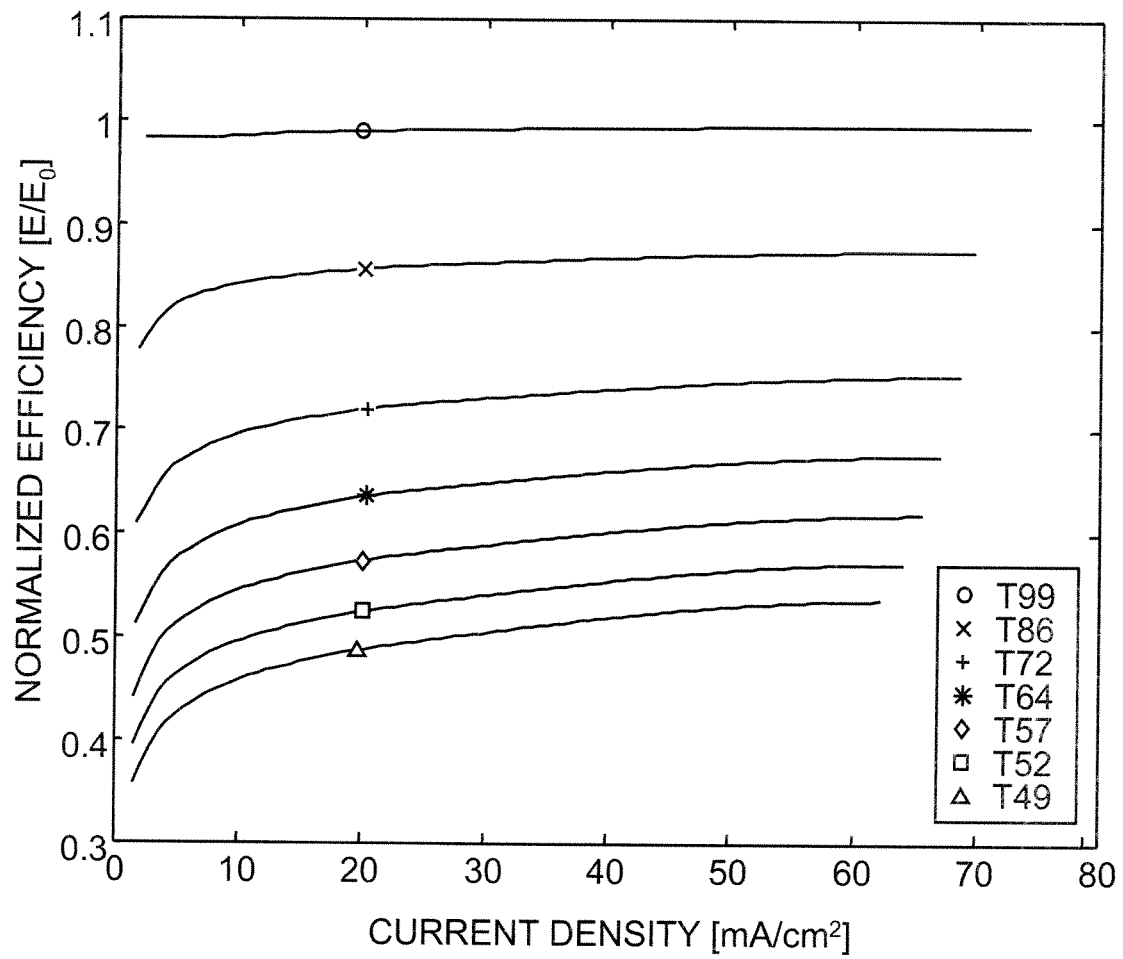


FIG. 10

**FIG. 11**

REFERENCES CITED IN THE DESCRIPTION

This list of references cited by the applicant is for the reader's convenience only. It does not form part of the European patent document. Even though great care has been taken in compiling the references, errors or omissions cannot be excluded and the EPO disclaims all liability in this regard.

Patent documents cited in the description

- US 4896947 A [0004]
- US 5034340 A, Tanaka [0004]
- US 20060273997 A, Nathan [0010]
- US 7199602 B, Nara [0010]
- US 6518962 B, Kimura [0010]
- US 20080048951 A, Naugler [0011]
- US 7116058 B, Lo [0012]
- US 6995519 B, Arnold [0013]
- US 6489631 B, Young [0014]
- US 20030057895 A1 [0015]
- US 20060214888 A1 [0016]
- WO 2005116971 A, Kawabe [0025]
- US 20080252653 A [0086]
- US 4769292 A, Tang [0092]
- US 5061569 A, VanSlyke [0092]

Non-patent literature cited in the description

- Thin-film Transistors. Marcel Dekker, 2003, 121-131 [0005]
- Organic Light-Emitting Devices: a survey. Springer-Verlag, 2004, 95-97 [0006]
- **MOHAN et al.** Stability issues in digital circuits in amorphous silicon technology. *Electrical and Computer Engineering*, 2001, vol. 1, 583-588 [0008]
- **LEE et al.** A New a-Si:H TFT Pixel Design Compensating Threshold Voltage Degradation of TFT and OLED. *SID 2004 Digest*, 264-274 [0009]
- **LURCH, N.** Fundamentals of electronics, 2e. John Wiley & Sons, 1971, 110 [0052]
- **GIORGIANNI ; MADDEN.** Digital Color Management: encoding solutions. Addison-Wesley, 1998, 283-295 [0075]

专利名称(译)	电致发光子像素补偿驱动信号		
公开(公告)号	EP2404292A1	公开(公告)日	2012-01-11
申请号	EP2010706863	申请日	2010-02-25
[标]申请(专利权)人(译)	全球OLED TECH		
申请(专利权)人(译)	全球OLED科技有限责任公司		
当前申请(专利权)人(译)	全球OLED科技有限责任公司		
[标]发明人	LEVEY CHARLES I HAMER JOHN W		
发明人	LEVEY, CHARLES, I. HAMER, JOHN, W.		
IPC分类号	G09G3/32		
CPC分类号	G09G3/3233 G09G2300/0842 G09G2320/0233 G09G2320/029 G09G2320/0295 G09G2320/043 G09G2320/045 G09G2360/16		
优先权	12/396662 2009-03-03 US		
其他公开文献	EP2404292B1		
外部链接	Espacenet		

摘要(译)

诸如有机发光二极管 (OLED) 子像素的电致发光 (EL) 子像素被补偿老化效应, 例如阈值电压 V_{th} 偏移, EL电压 V_{oled} 偏移和OLED效率损失。在一个或多个测量参考栅极电压下测量子像素的驱动电流, 以形成表示子像素的驱动晶体管和EL发射极的特性的状态信号。在驱动晶体管操作的线性区域中进行电流测量以改善诸如现代LTPS PMOS OLED显示器的系统中的信噪比, 其在其寿命期间具有相对小的 V_{oled} 偏移并且因此由于通道长度而具有相对小的电流变化。调制。还抑制了各种噪声源以进一步增加信噪比。