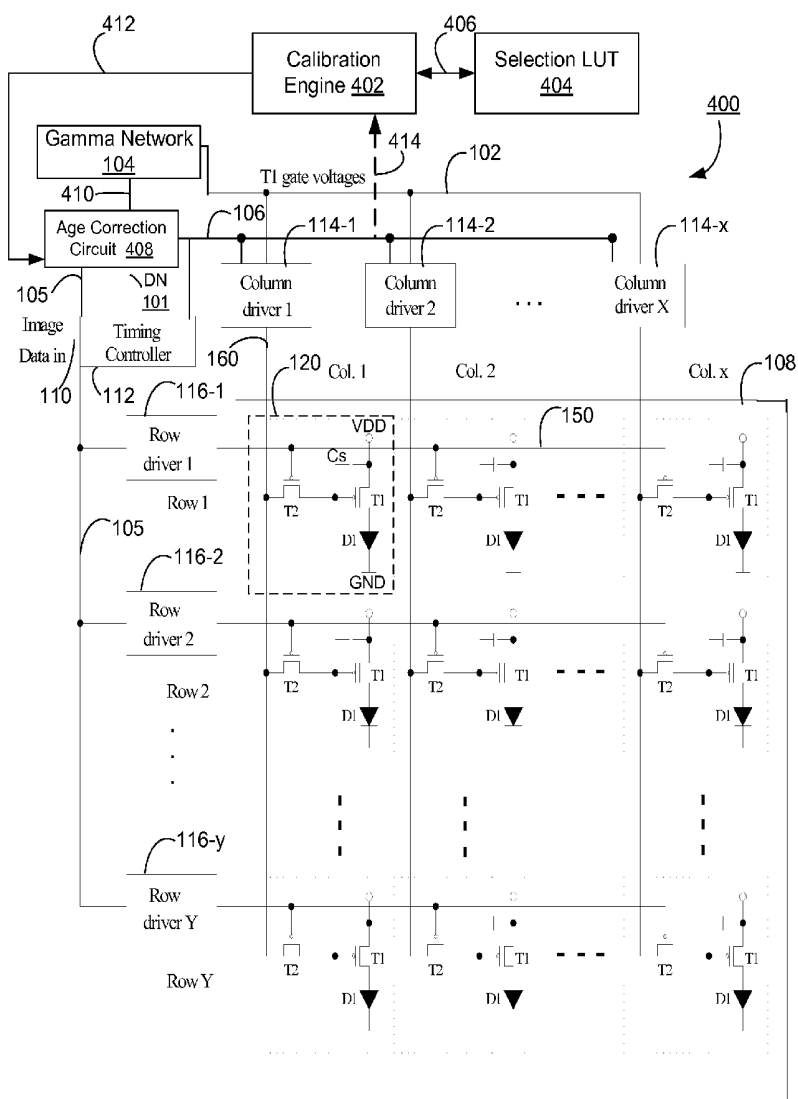




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(19) **United States**(12) **Patent Application Publication**
Naugler et al.(10) **Pub. No.: US 2008/0231557 A1**(43) **Pub. Date: Sep. 25, 2008**(54) **EMISSION CONTROL IN AGED ACTIVE
MATRIX OLED DISPLAY USING VOLTAGE
RATIO OR CURRENT RATIO**(22) Filed: **Mar. 18, 2008****Related U.S. Application Data**(75) Inventors: **Walter Edward Naugler, Katy, TX
(US); William Robert Bidermann,
San Diego, CA (US)**(60) Provisional application No. 60/919,195, filed on Mar.
20, 2007, provisional application No. 60/919,228,
filed on Mar. 20, 2007.**Publication Classification**(51) **Int. Cl.**
G09G 3/30 (2006.01)(52) **U.S. Cl.** **345/76**(57) **ABSTRACT**

Compensation needed to be made for reduced light efficiency in aged sub-pixels of an active matrix organic light-emitting diode (OLED) display are determined using a current ratio or a voltage ratio pertaining to an aged sub-pixel relative to un-aged, reference sub-pixels.

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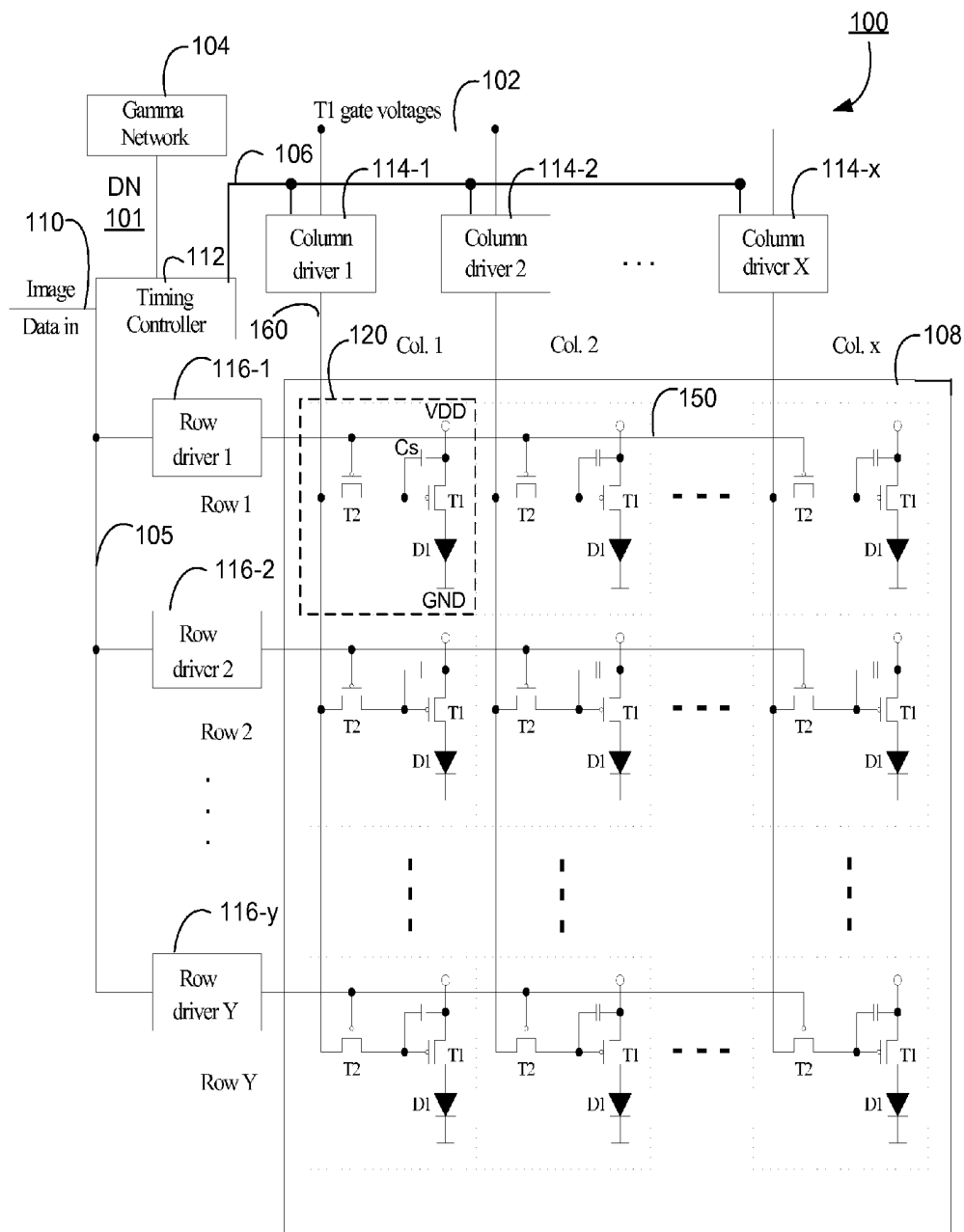


FIG. 1
(PRIOR ART)

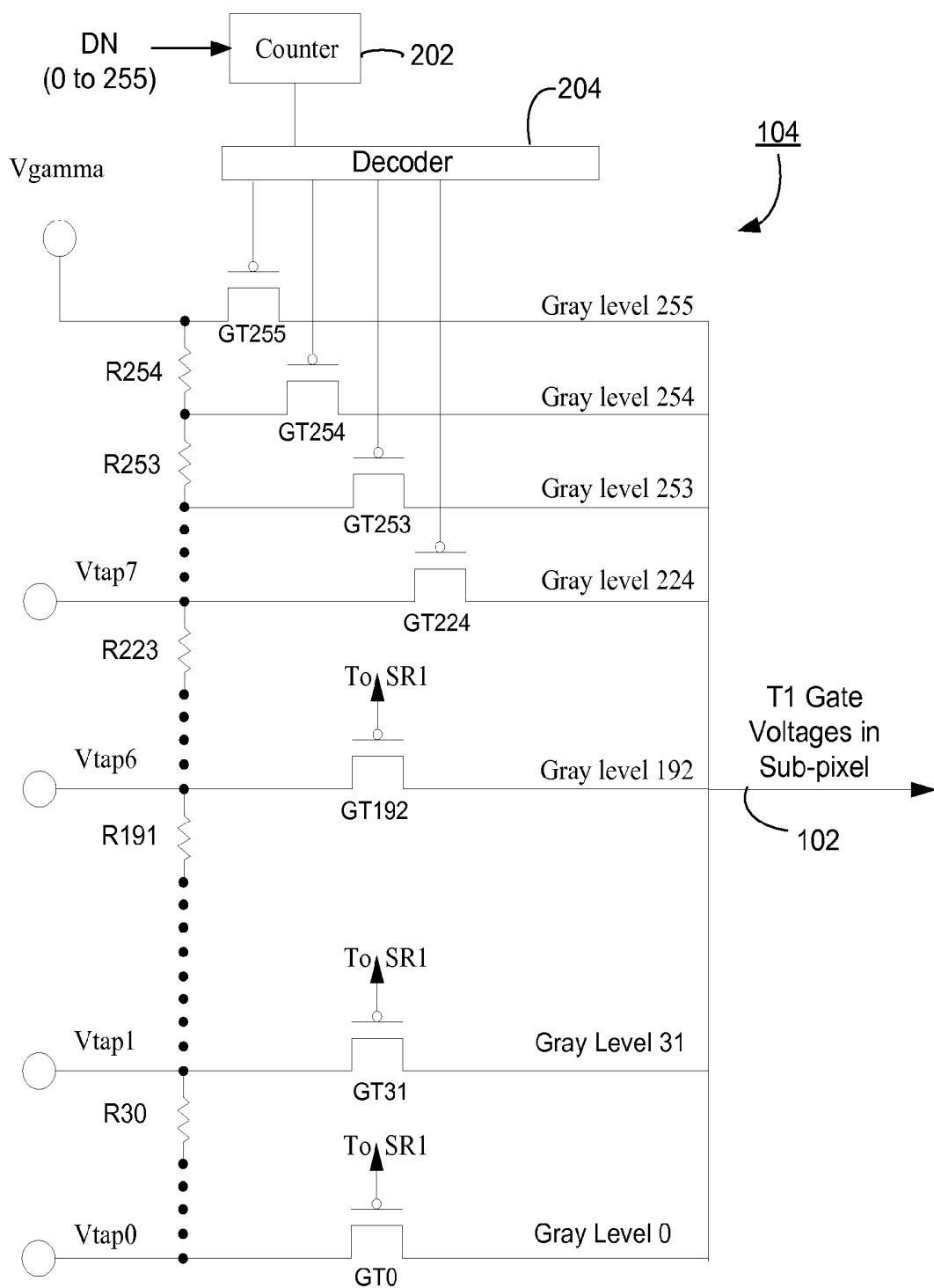


FIG. 2
(PRIOR ART)

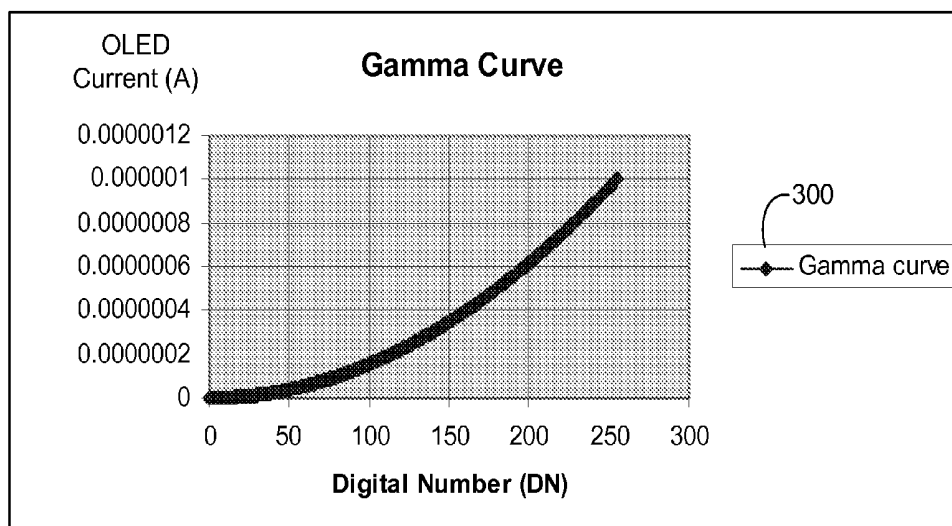


FIG. 3A
(PRIOR ART)

Table of Tap voltages and resistors					
	Volts	Resistor Group	Ohm	A	Resistor Range
Vtap0	1.541	Group 0	0	1.526E-11	
Vtap1	2.854	Group 1	7843	1.662E-08	R30 to R0
Vtap2	4.166	Group 2	7843	6.447E-08	R63 to R31
Vtap3	5.479	Group 3	7843	1.436E-07	R95 to R64
Vtap4	6.791	Group 4	7843	2.539E-07	R127 to R96
Vtap5	8.104	Group 5	7843	3.955E-07	R159 to R128
Vtap6	9.416	Group 6	7843	5.684E-07	R191 to R160
Vtap7	10.729	Group 7	7843	2.384E-07	R223 to R192
V gamma	12.000	Group 8	7843	1.00E-06	R254 to R224

FIG. 3B
(PRIOR ART)

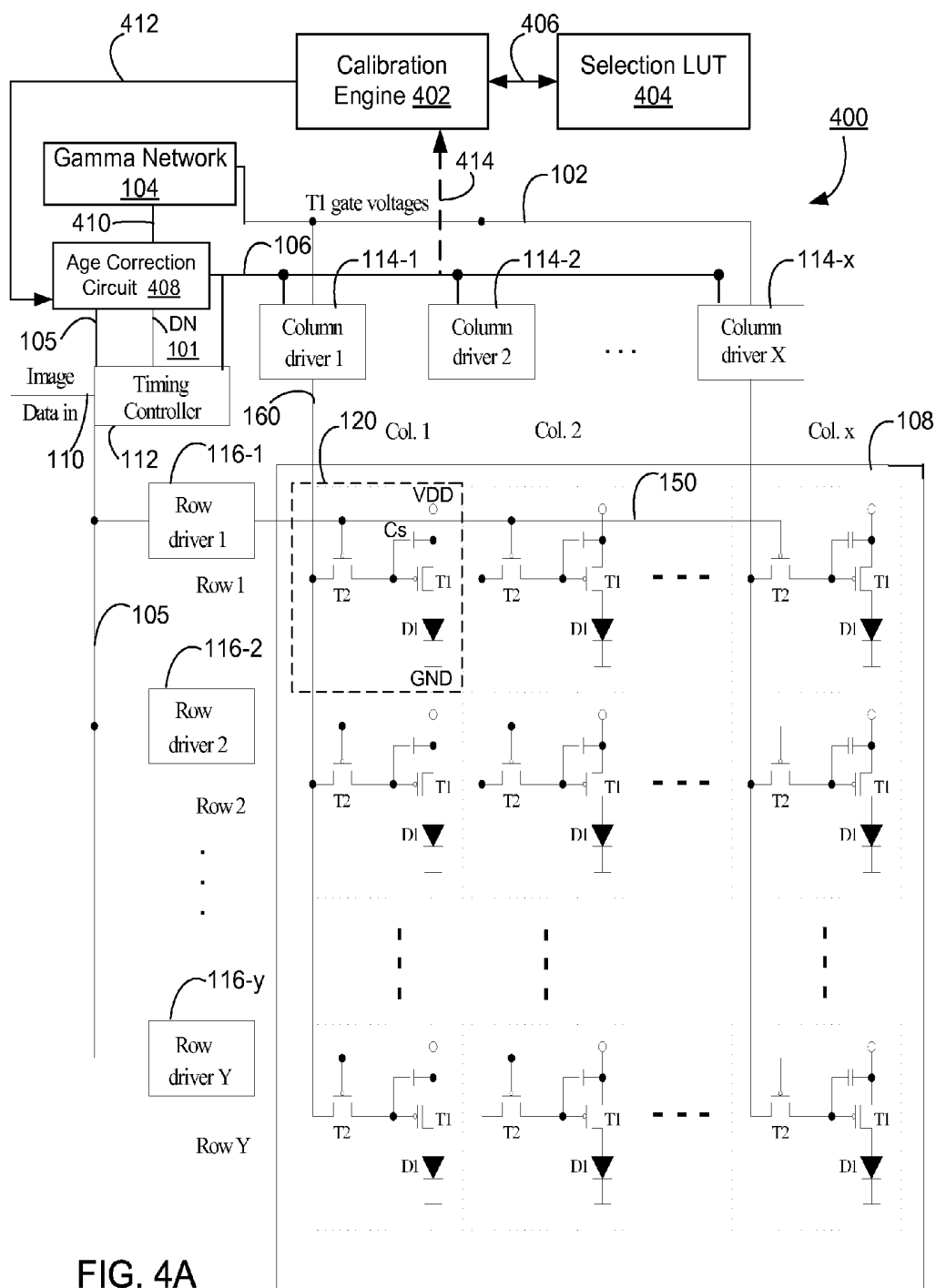


FIG. 4A

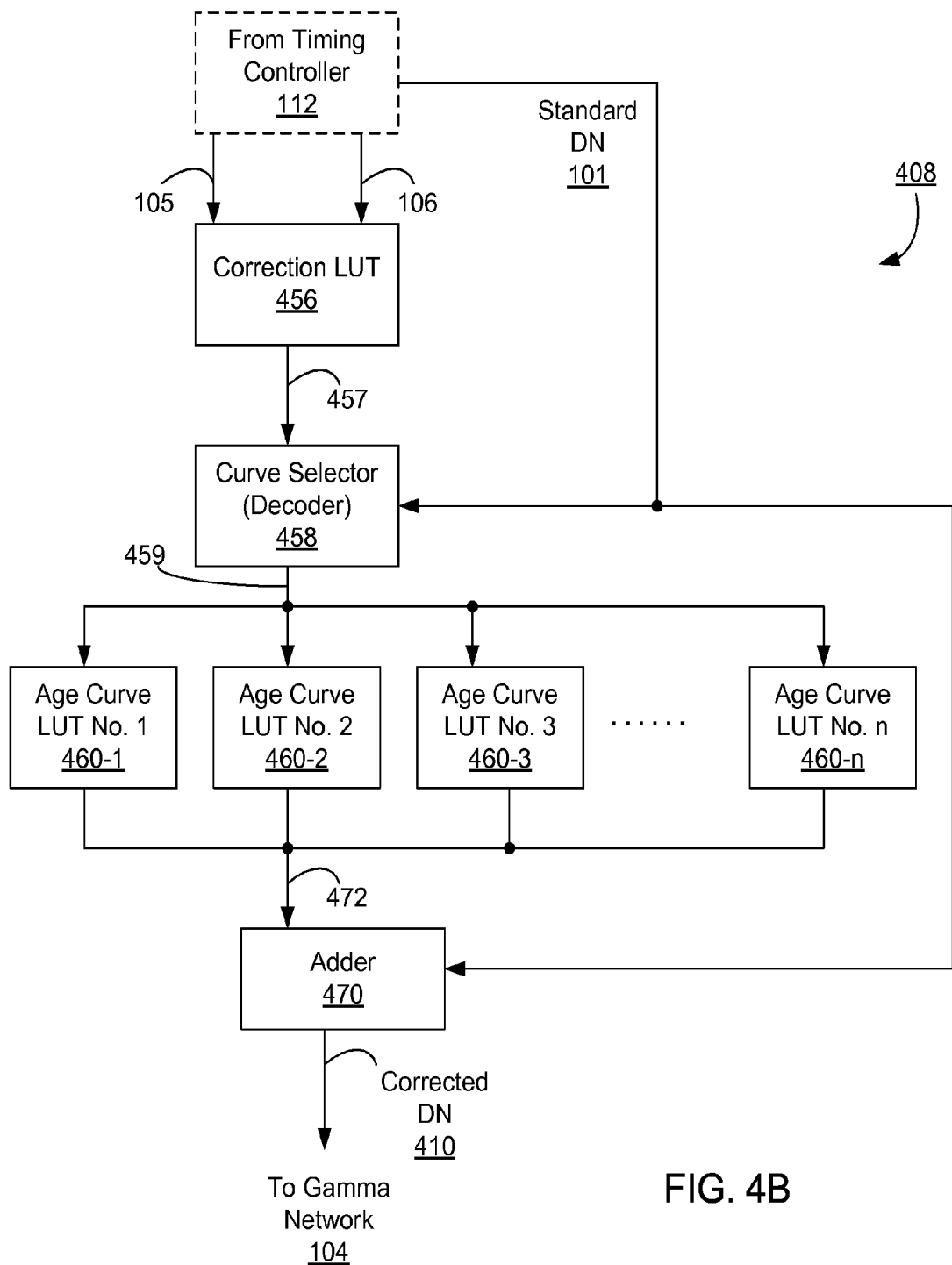


FIG. 4B

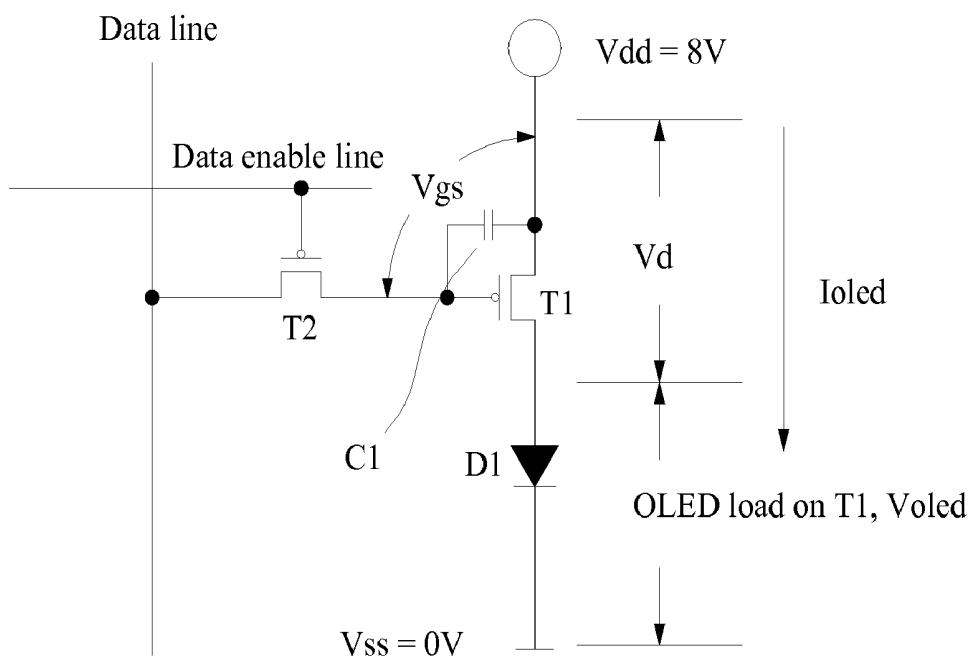


FIG. 5A

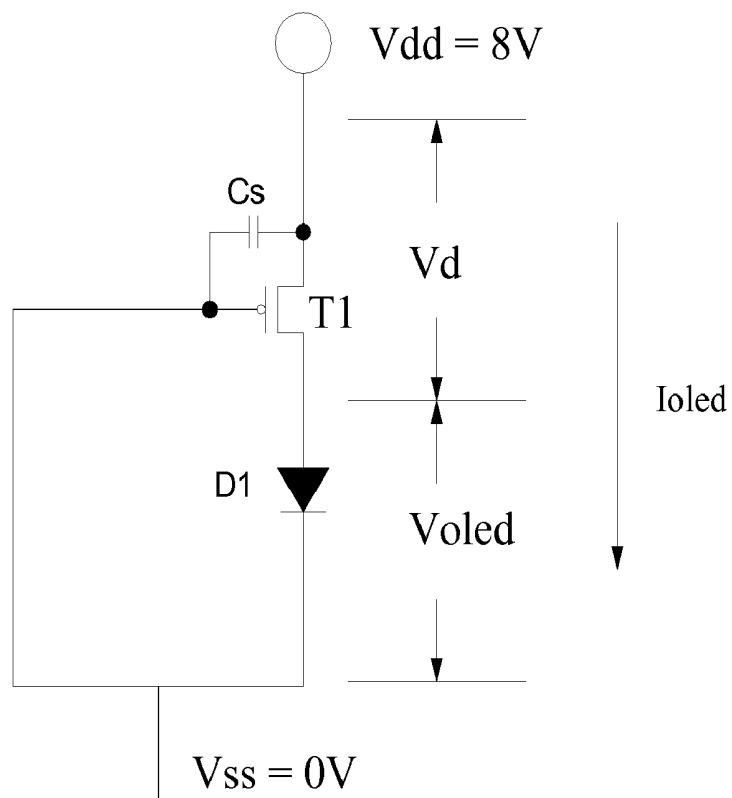


FIG. 5B

600

3250 Hours <u>626</u>	3500 Hours <u>628</u>	3750 Hours <u>630</u>	4000 Hours <u>632</u>
2250 Hours <u>618</u>	2500 Hours <u>620</u>	2750 Hours <u>622</u>	3000 Hours <u>624</u>
1250 Hours <u>610</u>	1500 Hours <u>612</u>	1750 Hours <u>614</u>	2000 Hours <u>616</u>
250 Hours <u>602</u>	500 Hours <u>604</u>	750 Hours <u>606</u>	1000 Hours <u>608</u>
Reference Pixels (Not Aged) <u>632</u>			

FIG. 6

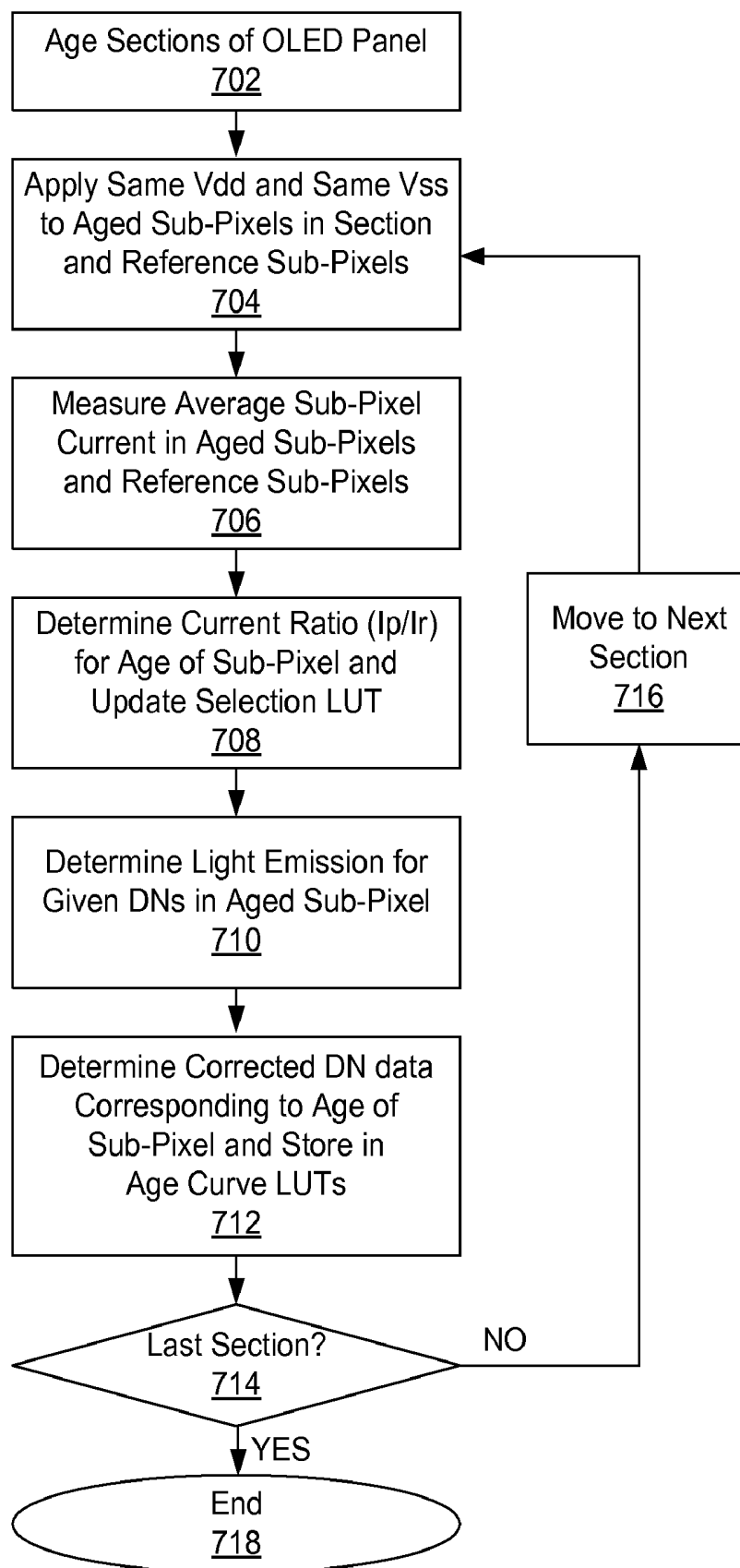


FIG. 7A

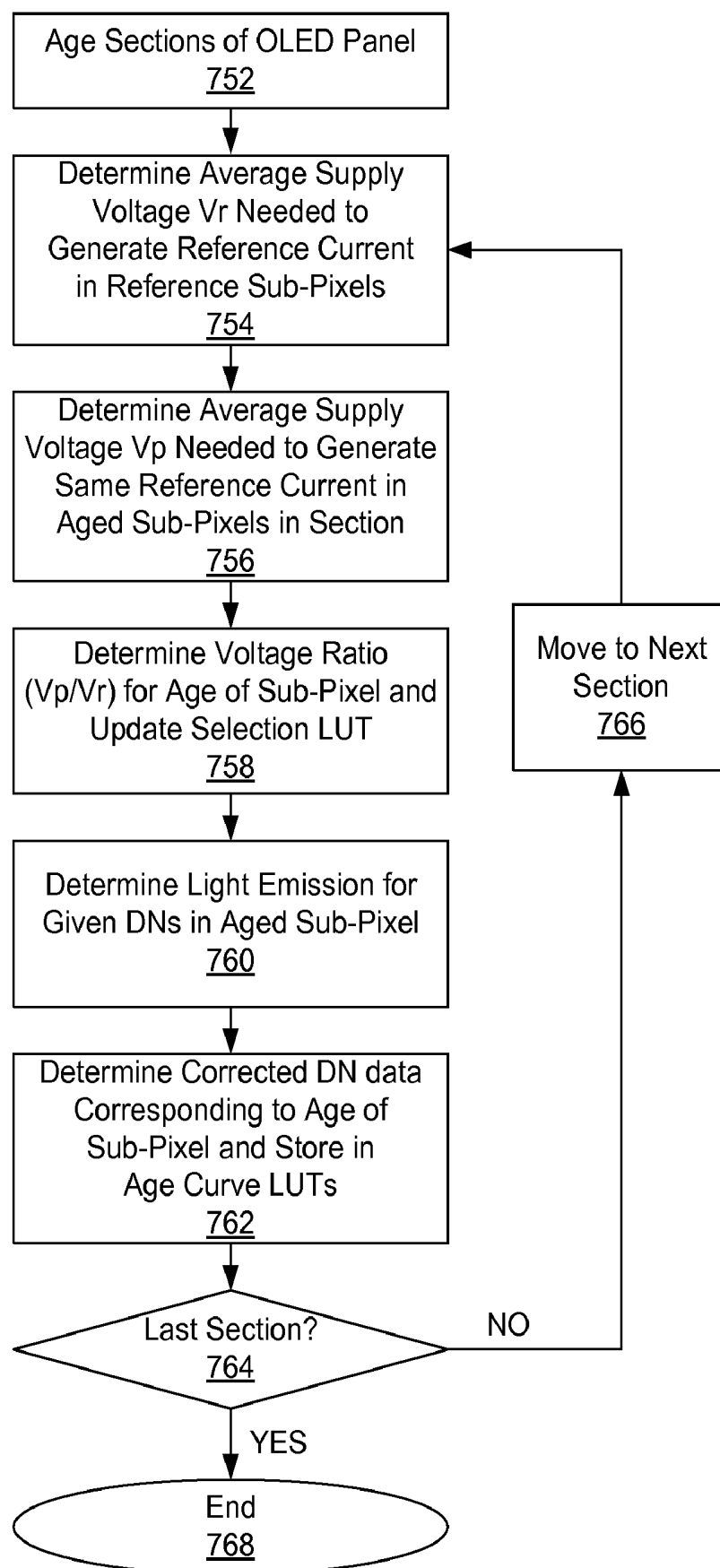


FIG. 7B

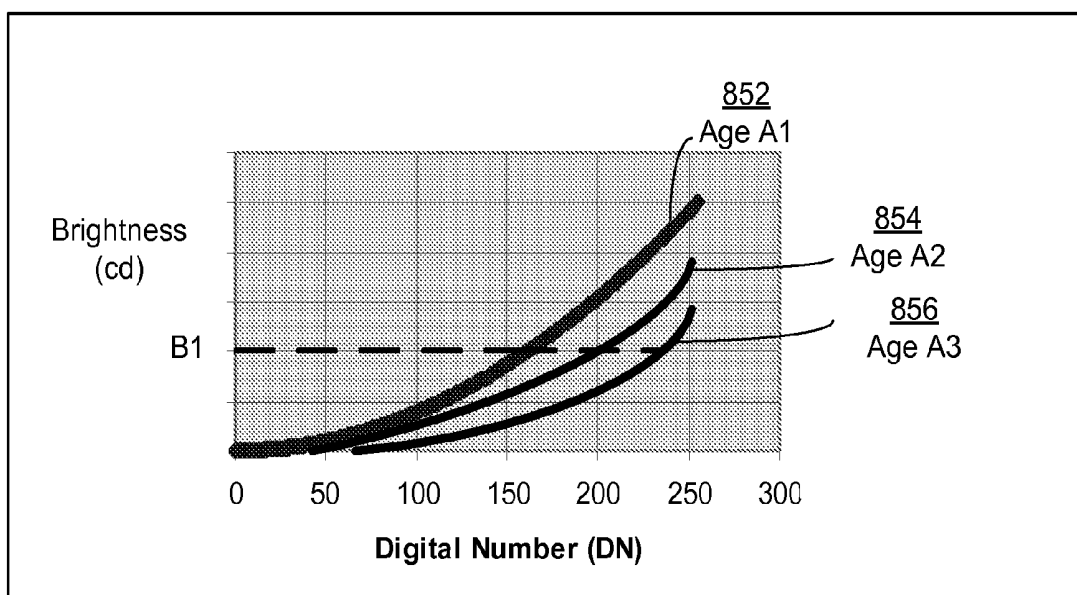


FIG. 8

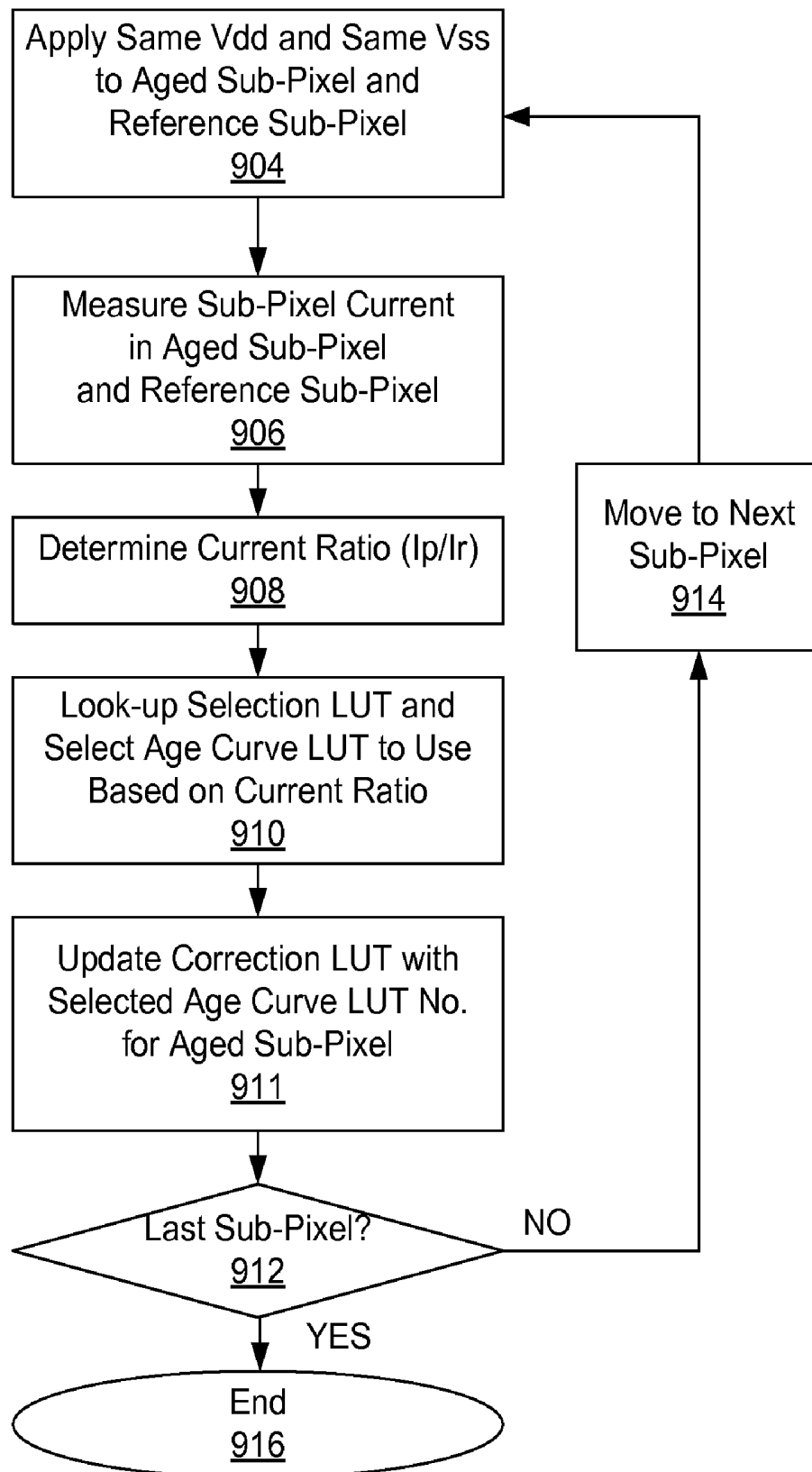


FIG. 9A

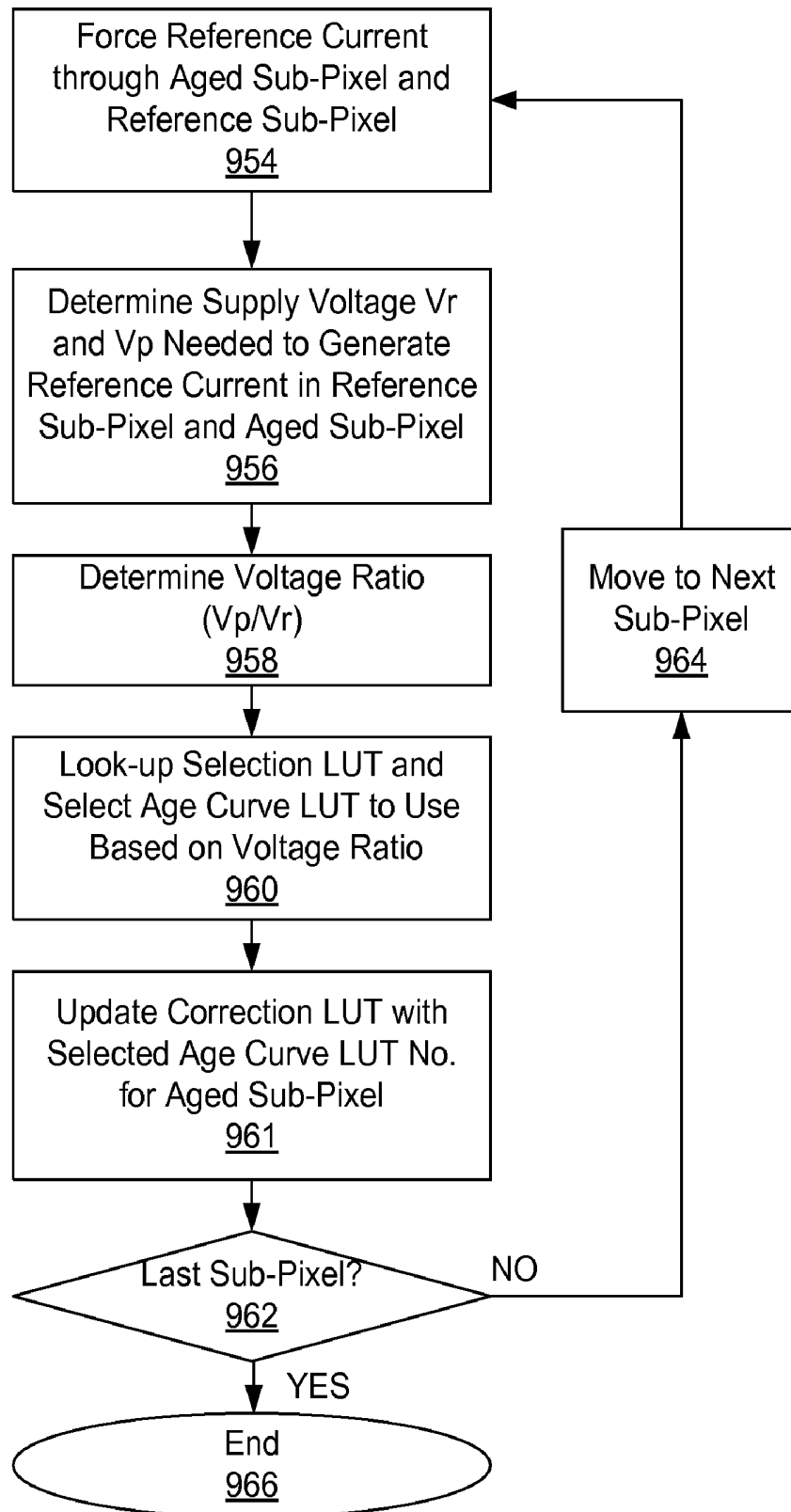


FIG. 9B

EMISSION CONTROL IN AGED ACTIVE MATRIX OLED DISPLAY USING VOLTAGE RATIO OR CURRENT RATIO

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] This application claims priority under 35 U.S.C. §119(e) from (i) co-pending U.S. Provisional Patent Application No. 60/919,195 entitled “Method for Emission Control for Pixels in an Active Matrix Emissive Display Using Current Ratios,” filed on Mar. 20, 2007 and (ii) co-pending U.S. Provisional Patent Application No. 60/919,228 entitled “Method for Emission Control for Pixels in an Active Matrix Emissive Display Using Voltage Ratios,” filed on Mar. 20, 2007, both of which are incorporated by reference herein in their entirety.

BACKGROUND OF THE INVENTION

[0002] 1. Field of the Invention

[0003] The present invention relates to modifying the current fed to an aging OLED sub-pixel in order to maintain constant light emission at a desired gray level.

[0004] 2. Description of the Related Arts

[0005] An OLED display is generally comprised of an array of organic light emitting diodes (OLEDs) that have carbon-based films disposed between two charged electrodes. Generally one electrode is comprised of a transparent conductor, for example, indium tin oxide (ITO). Generally, the organic material films are comprised of a hole-injection layer, a hole-transport layer, an emissive layer and an electron-transport layer. When voltage is applied to the OLED, the injected positive and negative charges recombine in the emissive layer and transduce electrical energy to light energy. Unlike liquid crystal displays (LCDs) that require backlighting, OLED displays are self-emissive devices—they emit light rather than modulate transmitted or reflected light.

[0006] An OLED display typically includes a plurality of OLEDs arranged in a matrix form including a plurality of rows and a plurality of columns, with the intersection of each row and each column forming a pixel of the OLED display. An OLED display is generally activated by way of a current driving method that relies on either a passive-matrix (PM) scheme or an active-matrix (AM) scheme.

[0007] In a passive matrix OLED display, a matrix of electrically-conducting rows and columns forms a two-dimensional array of picture elements called pixels. Sandwiched between the orthogonal column and row lines are thin films of organic material of the OLEDs that are activated to emit light when current is applied to the designated row and column lines. The brightness of each pixel is proportional to the amount of current applied to the OLED of the pixel. While PMOLEDs are fairly simple structures to design and fabricate, they demand relatively expensive, current-sourced drive electronics to operate effectively and are limited as to the number of lines because only one line can be on at a time and therefore the PMOLED must have instantaneous brightness equal to the desired average brightness times the number of lines. Thus, PMOLED displays are typically limited to under 100 lines. In addition, their power consumption is significantly higher than that required by an active-matrix OLED. PMOLED displays are most practical in alpha-numeric displays rather than higher resolution graphic displays.

[0008] An active-matrix OLED (AMOLED) display is comprised of OLED pixels that have been deposited or integrated onto a thin film transistor (TFT) array to form a matrix of pixels that emit light upon electrical activation. In contrast to a PMOLED display, where electricity is distributed row by row, the active-matrix TFT backplane acts as an array of switches coupled with sample and hold circuitry that control and hold the amount of current flowing through each individual OLED pixel during the total frame time. The active matrix TFT array continuously controls the current that flows to the OLEDs in the each of pixels, signaling to each OLED how brightly to illuminate.

[0009] FIG. 1 illustrates a conventional active matrix OLED display. While the example of FIG. 1 is illustrated as an OLED display, other emissive-type displays would have structures similar to that illustrated in FIG. 1. Referring to FIG. 1, the OLED display panel includes a plurality of rows Row 1, Row 2, . . . , Row Y and a plurality of columns Col. 1, Col. 2, . . . , Col. X arranged in a matrix. The intersection of each row and each column forms a pixel of the OLED display. The OLED display also includes a Gamma network 104, row drivers 116-1, 116-2, . . . , 116-y, column drivers 114-1, 114-2, . . . , 114-x, and a timing controller 112.

[0010] For a color OLED display, each pixel includes 3 sub-pixels that have similar structure but emit different colors (R, G, B). For simplicity of illustration, FIG. 1 illustrates only one sub-pixel (denoted as dashed line boxes in FIG. 1, such as box 120) corresponding to one of the R, G, B colors per pixel at the intersection of each row and each column. However, in real OLED display panels, each pixel includes three identical ones of the sub-pixel structure 120 as illustrated in FIG. 1. As shown in FIG. 1, the active drive circuitry of each sub-pixel 120 includes TFTs T1 and T2 and a storage capacitor Cs for driving the OLED D1 of the sub-pixel 120. In the following explanation of FIG. 1, the type of the TFTs T1 and T2 is a p-channel TFT. However, note that n-channel TFTs may also be utilized in the active matrix.

[0011] Image data 110 includes data indicating which sub-pixel 120 of the OLED display should be turned on and the brightness of each sub-pixel. Image data 110 is sent by an image rendering device (e.g., graphics controller (not shown herein)) to the timing controller 112, which coordinates column and row timing. The timing controller 112 sends digital numbers (DN) 101 indicating pixel brightness to the gamma network 104. Row timing data 105 included in image data 110 is coupled to the gate lines 150 of each row through its corresponding row driver 116-1, 116-2, . . . , 116-y. Row drivers 116-1, 116-2, . . . , 116-y drive the gate line 150 so that the gate lines 150 carry a voltage of 25 to 30 volts when active. The gates of TFTs T2 of each sub-pixel in a row are connected to gate line 150 of each row to enable TFTs T2 to operate as switches. The data lines 160 are connected to the sources of TFTs T2 in each column. When the gate line 150 becomes active for a row based on the row timing data 105, all the TFTs T2 in the row are turned on. Timing controller 112 sends column timing data 106 to the column drivers 114-1, 114-2, . . . , 114-x. The Gamma network 104 generates the T1 gate voltages 102 (brightness) to be applied to each TFT T1 in the row when the sub-pixel 120 is turned on, based on digital numbers (DNs) 101 corresponding to each gate voltage 102. Column drivers 114-1, 114-2, . . . , 114-x provides analog voltages 160 to be applied to the gates of TFTs T1, corresponding to the T1 gate voltages 102. The voltages 102 representing pixel brightness values are distributed from the

Gamma network 104 to all the column drivers 114-1, 114-2, . . . , 114-x in parallel after the appropriate T1 gate voltages 102 have been sent from gamma network 104 to each column driver 114-1, 114-2, . . . , 114-x under control of the column timing data 106 from timing controller 112. Under control of the timing controller 112, for example, row driver 1 (116-1) is activated and all the voltages 102 placed on the column drivers 114-1, 114-2, . . . , 114-x are downloaded to the TFT T1s in row 1. Timing controller 112 then proceeds to send brightness data for the next row (e.g., row 2) using the row driver 2 (116-2) to column drivers 114-1 through 114-x and activating row 2 and so forth, until all rows have been activated and brightness data for the total frame has been downloaded and all the sub-pixels are turned on to the brightness indicated by the image data 110.

[0012] The drain of TFT T2 is connected to the gate of TFT T1 and to one side of storage capacitor Cs. The source of TFT T1 is connected to positive supply voltage VDD. The other side of storage capacitor Cs is also connected, for example, to the positive supply voltage VDD and to the source of TFT T1. Note that the storage capacitor Cs may be tied to any reference electrode in the pixel. The drain of TFT T1 is connected to the anode of OLED D1. The cathode of OLED D1 is connected to negative supply voltage Vss or common Ground. The analog voltages 160 are downloaded to the OLED display a row at a time.

[0013] When TFT T2 is turned on, the analog T1 gate voltage 160 is applied to the gate of each TFT T1 of each sub-pixel 120, which is locked by storage capacitor Cs. When the row scan moves to the next row, the gate voltage of TFT T1 is locked for the frame time until the next gate voltage for that sub-pixel is sent by the column drivers 114-1, 114-2, . . . , 114-n. In other words, the continuous current flow to the OLEDs is controlled by the two TFTs T1, T2 of each sub-pixel. TFT T2 is used to start and stop the charging of storage capacitor Cs, which provides a voltage source to the gate of TFT T1 at the level needed to create a constant current to the OLED D1. As a result, the AMOLED display operates at all times (i.e., for the entire frame scan), avoiding the need for the very high instantaneous currents required for passive matrix operation. The TFT T2 samples the data on the data line 160, which is held as charge stored in the storage capacitor Cs. The voltage held on the storage capacitor Cs is applied to the gate of the second TFT T1. In response, TFT T1 drives current through the OLED D1 to a specific brightness depending on the value of the sampled and held data signal as stored in the storage capacitor Cs.

[0014] FIG. 2 illustrates a conventional gamma network used with an active matrix OLED display. The gamma network 104 is a circuit that converts the brightness data for a sub-pixel from a digital number (DN) representing the desired gray level (brightness) to an analog voltage, which will produce the right amount of current to drive OLED D1 to emit the desired brightness when the analog voltage 160 is applied to the gate of TFT T1 in the sub-pixel 120 (See FIG. 1). For example, the gamma network 104 in FIG. 2 is a conventional 8 bit gamma network used with DN (8 bits) ranging from 0 to 255. Gamma network 104 includes a counter 202, a decoder 204, a series of resistors (R0, . . . , R30, . . . R191, . . . , R223, . . . , R253, R254) (255 resistors for an 8 bit system) and 256 switches GT0, GT1, . . . , GT255. The gate of each switch GT0, GT1, . . . , GT255 is coupled to the corresponding one of the bits of decoder 204. When the corresponding binary bit at the decoder 204 is "1" the corre-

sponding switch (GT0, GT1, . . . , GT255) is turned on, and when the binary bit at the decoder 204 is "0" the corresponding switch (GT0, GT1, GT255) is turned off. DN 101 can be any value between 0 and 255 for an eight bit system. Counter 202 counts up to the value of DN 101 sent to the Gamma network 104, causing decoder 204 to move its output to the gate of the gamma table switches GT(DN). For example, if a DN of 185 indicating brightness level 185 was sent to counter 202, decoder 204 would move its output to GT185, thereby switching switch GT185 on. Gamma network 104 is essentially a voltage divider with 256 taps corresponding to 256 gray levels (brightnesses). The voltage at tap 185 is controlled by switch GT 185, which when turned on delivers to the gate of the TFT T1 in the specified sub-pixel the voltage calculated to produce a gray level brightness corresponding to DN 185.

[0015] The voltage 102 output from the gamma network 104 is designed to produce a series of currents from TFT T1 that will produce 256 levels (in an 8 bit display system) of light emission from OLED D1 conforming to the brightness response of the human eye. The human eye is logarithmically sensitive to brightness and thus approximately has a linear response approximate to the square of brightness. That is, for the human eye to experience a doubling of brightness, the light flux has to be increased approximately 4 times. This relationship of eye response to light flux (brightness) is known as the gamma function (γ), which is not exactly 2 but closer to 2.2. In general, gamma gives contrast to the image. If, for example, gamma is reduced to 1 (a linear relationship between eye response and light), the images produced would have very low contrast, and be flat and very uninteresting. If gamma is increased, contrast of the image increases. Note that gamma refers to the relationship between the eye and light—not current or voltages. OLED emission is produced by current flowing through OLED D1 as controlled by TFT T1. Thus, it is the function of the gamma network 104 to produce an appropriate voltage, which will produce appropriate current through OLED D1, which will produce light with the correct (or desired) gamma function. The emission of light from OLED material is linear to the current. That is, in order to double the luminance (expressed as cd/m^2 —candelas per meter squared), current is doubled.

[0016] The brightness values in an image are represented as digital numbers (DNs). For an 8-bit display system, DN's range from 0 to 255. The light values are called gray scale levels and are linear to the human eye. Thus, a doubling of DN's is perceived by the human eye as a doubling of brightness. The gamma relation between DN's and the current of TFT T1 can be determined as follows. FIG. 3A illustrates the gamma curve showing the relationship between the digital number (DN) and the OLED current. Note that gamma curve 300 is not linear but has a curve with a changing slope. The exact shape of the gamma curve 300 is determined by the desired gamma. The gamma curve 300 shown in FIG. 3A is for a gamma of 2.

[0017] FIG. 3B is a table showing example resistors, voltages and currents for the gamma network in FIG. 2. Referring to FIGS. 2 and 3B, note that the resistors (R0 through R254) are grouped with roughly 32 resistors per group, except Group 0 that includes no resistor, although all the resistors are not shown in FIG. 2 for simplicity of illustration. Each resistor group (Group 0 through Group 8) is associated with a tap voltage Vtap0 through Vtap7 and Vgamma. The tap voltages, for example, are bounded by a minimum voltage (1.541 volts) and a maximum voltage (Vgamma, 12.000 volts). The tap

voltages coupled with the minimum and maximum voltages establish the gamma current curve **300** with the aid of resistors **R0** through **R254**. The tap voltages are voltage sources, and thus the voltage established between each resistor is determined by the current drawn between the tap voltages. The greater the number of tap voltages, the better current conformation is to the gamma curve. In the example of FIG. **3B**, nine voltage sources produce the voltages at each resistor (**R0** through **R254**), which in turn use TFT **T1** to produce the current that conforms to the gamma curve **300**. By adjusting the tap voltages, the gamma current curve **300** will change.

[0018] The gate voltage **102** to the TFT **T1** is determined by the tap voltages, resistors, and which of the switches **GT0**, . . . , **GT255** is turned on. For example, when **DN** is **255**, counter **202** moves the output of decoder **204** to the gate line for **GT255**; thereby connecting **Vgamma** voltage to line **102** which connects to the column driver of the selected sub-pixel. Since the **Vgamma** voltage is the maximum voltage put out by the Gamma Network **104**, the maximum voltage is placed on the gate of **T1** in the selected sub-pixel. This maximum voltage causes TFT **T1** in the selected sub-pixel to supply the current to OLED **D1** for the brightest gray level for the sub-pixel. The voltage value of **Vgamma** is determined by the design of **T1** and the designed top brightness of the sub-pixel. The methods of doing such design work are well known in the display industry. The table in FIG. **3B** is an example of design voltages for **Vgamma** and the taps on the voltage divider. For example, the design voltage for **Vgamma** from FIG. **3B** is **12 V**. As a further example, if the sub-pixel is scheduled by the image data to be black (off) then **DN 0** is sent to the gamma network **104** causing counter **202** to move the output of decoder **204** to switch **GT0** connecting **Vtap0** to the output line **102**. The voltage value of **Vtap0** from the table in FIG. **3B** is **1.541 Volts**, which when supplied to the gate of **T1** through the column driver for the selected sub-pixel causes the current supplied to OLED **D1** to be less than the threshold current for OLED **D1** and therefore, no light will be emitted from the sub-pixel for the frame. The taps on the gamma network voltage divider **104** will be between **Vgamma** and **Vtap0** (**12 Volts** and **1.541 Volts**, respectively, in the example). As a further example, if **DN 227** is sent to gamma network **104**, counter **202** will move the output of decoder **204** to the gate line for switch **GT227** connecting to the aforesaid voltage divider **104** at a point between **Vgamma** and **Vtap7**. The exact voltage connected through switch **GT227** to output line **102**, and thus, to the gate of TFT **T1** in the selected sub-pixel will be determined by the voltage drop from **Vgamma** to **Vtap7**, which from the table in FIG. **3B** is determined to be **12 Volts–10.729 Volts=1.271 Volts**. There are **31 resistors (255–224=31)** between **Vgamma** and **Vtap7**; therefore, the voltage is dropped in **31 equal decrements** from **Vgamma** to **Vtap**, because all **31 resistors** are of the same value, which from the FIG. **3B** is **7843 Ohms** each. Each voltage drop, therefore, is **1.271/31=0.041 volts**. There are **28 resistors (255–227)** between the **GT227** tap and the **GT255** tap; therefore, the voltage drop is **28×0.041=1.148 Volts**. The exact voltage sent to the selected sub-pixel through output line **102** and the column driver to the gate of TFT **T1** is **12 volts–1.148 Volts=10.852 Volts**, which is the **T1 gate voltage** designed to supply the required current to OLED **D1** to emit brightness corresponding to gray level **227**. The other voltages at the various gray levels are calculated in the same manner.

[0019] Referring back to FIG. **1**, the OLED display **100** requires regulated current in each sub-pixel to produce a

desired brightness from the pixel. Ideally, the TFTs **T1** in each sub-pixel **120** should be good current sources that deliver the same current for the same gate voltage over the lifetime of the OLED display. Also each current source TFT **T1** in the active TFT matrix must deliver the same current for the same data voltage stored in the storage capacitor **Cs** in order that the display is uniform.

[0020] Note that there are two types of thin film semiconductors in popular use in the active matrix display industry: amorphous silicon (a-Si) and poly-silicon (p-Si). Emissive displays, such as the active matrix OLED (AMOLED) displays, require high current and stability not available in the a-Si TFTs and therefore typically use p-Si for the TFTs **T1**, **T2**. a-Si is converted to p-Si by laser annealing the a-Si to increase the crystal grain size and thus convert a-Si to p-Si. The larger the crystal grain size, the faster and more stable is the resulting semiconductor material. Unfortunately the grain size produced in the laser anneal step is not uniform due to a temperature spread in the laser beam. Thus, uniform TFTs **T1**, **T2** are very difficult to produce and thus the current supplied by TFTs **T1** in conventional OLED displays is often non-uniform, resulting in non-uniform display brightness. Non-uniform TFTs **T1** throughout the OLED display causes “Mura” or streaking in the OLED displays made with p-Si TFTs. In other words, TFTs **T1** may produce different OLED current due to its non-uniformities from sub-pixel to sub-pixel, even if the same gate voltage is applied to the TFTs **T1**. Therefore, it is necessary to compensate for non-uniformities in the TFTs **T1** by applying corrected (compensated) **T1** gate voltages that are different from the intended gate voltage from the graphics board (not shown) to the TFTs **T1**. This can be done by measuring the gray level (gate voltage) versus current characteristics of the TFTs **T1** for each sub-pixel, and using such current measurement data to compensate for the non-uniformities in TFTs **T1** when driving the TFTs **T1** with the gate voltage **102** through the gamma network **104**.

[0021] Another problem with AMOLED displays occurs due to aging of the material in the OLEDs. As the OLED sub-pixels age with use, OLEDs become less efficient in converting current to light, i.e., the efficiency of light emission of the OLEDs decreases. Thus, as OLED current to light efficiency of the OLED material decreases with use (age), light emitted from an OLED sub-pixel for a given **DN** number also decreases, because the gamma network **104** in conventional AMOLED does not compensate for the decreased efficiency of light emission in the aged OLED sub-pixels. As a result, the OLED display emits less light for display than desired in response to a given **DN**. In addition, since the OLED sub-pixels on various parts of the AMOLED display do not age (are not used) equally in a uniform manner, OLED aging also causes non-uniformity in the OLED display.

[0022] Thus, there is a need to solve problems associated with aging of the OLED sub-pixels.

SUMMARY OF THE INVENTION

[0023] Embodiments of the present invention include methods of determining the amount of compensation needed for reduced light efficiency in aged sub-pixels of an active matrix organic light-emitting diode (OLED) display, using a current ratio or a voltage ratio pertaining to an aged sub-pixel relative to un-aged, reference sub-pixels.

[0024] In one embodiment, the method comprises aging a plurality of sections of sub-pixels of the active matrix OLED display, with the sections including at least a first section

including aged sub-pixels and a second section including reference sub-pixels that are not aged, applying a predetermined voltage across one of the aged sub-pixels and at least one of the reference sub-pixels, determining a first current through said one of the aged sub-pixels and a second current through said at least one of the reference sub-pixels, determining an age of said one of the aged sub-pixels based on the first current relative to the second current, determining light emission characteristics of said one of the aged sub-pixels, and determining corrections to be made to digital numbers indicative of desired brightness in said one of the aged sub-pixels based on mappings between the determined age and the determined light emission characteristics of said one of the aged sub-pixels.

[0025] In another embodiment, the method comprises aging a plurality of sections of sub-pixels of the active matrix OLED display, with the sections including at least a first section including aged sub-pixels and a second section including reference sub-pixels that are not aged, determining a first voltage applied to one of the aged sub-pixels to generate a predetermined reference current through said one of the aged sub-pixels, determining a second voltage applied to one or more of the reference sub-pixels to generate the same predetermined reference current through said one or more of the reference sub-pixels, determining an age of said one of the aged sub-pixels based on the first voltage relative to the second voltage, determining light emission characteristics of said one of the aged sub-pixels, and determining corrections to be made to digital numbers indicative of desired brightness in said one of the aged sub-pixels based on mappings between the determined age and the determined light emission characteristics of said one of the aged sub-pixels.

[0026] According to the present invention, it is possible to conveniently determine the age of an aged sub-pixel relative to an un-aged reference sub-pixel using voltage ratios or current ratios, and correlate such age measurement with the correction that needs to be made to the DNs in order to compensate for reduced light efficiency of the aged sub-pixels of the OLED display.

[0027] The features and advantages described in the specification are not all inclusive and, in particular, many additional features and advantages will be apparent to one of ordinary skill in the art in view of the drawings, specification, and claims. Moreover, it should be noted that the language used in the specification has been principally selected for readability and instructional purposes, and may not have been selected to delineate or circumscribe the inventive subject matter.

BRIEF DESCRIPTION OF THE DRAWINGS

[0028] The teachings of the embodiments of the present invention can be readily understood by considering the following detailed description in conjunction with the accompanying drawings.

[0029] FIG. 1 illustrates a conventional active matrix OLED display.

[0030] FIG. 2 illustrates a conventional gamma network used with an active matrix OLED display.

[0031] FIG. 3A illustrates a gamma curve showing the relationship between the digital number (DN) and the OLED current.

[0032] FIG. 3B is a table showing example resistors, voltages and currents for the gamma network in FIG. 2.

[0033] FIG. 4A illustrates an active matrix OLED display, according to one embodiment of the present invention.

[0034] FIG. 4B illustrates the age correction circuit shown in FIG. 4A in more detail, according to one embodiment of the present invention.

[0035] FIGS. 5A and 5B illustrate a sub-pixel of the AMOLED display in more detail.

[0036] FIG. 6 illustrates how an AMOLED display is aged, according to one embodiment of the present invention.

[0037] FIG. 7A illustrates a method of determining corrected digital numbers (DNs) to use with aged sub-pixels of an AMOLED display using current ratios, according to one embodiment of the present invention.

[0038] FIG. 7B illustrates a method of determining corrected digital numbers (DNs) to use with aged sub-pixels of an AMOLED display using voltage ratios, according to one embodiment of the present invention.

[0039] FIG. 8 illustrates the relationship between OLED brightness and digital numbers (DNs) for different ages of the OLEDs, according to one embodiment of the present invention.

[0040] FIG. 9A illustrates a method of determining the appropriate age curve look-up table (LUT) to use for age compensation using current ratios, according to one embodiment of the present invention.

[0041] FIG. 9B illustrates a method of determining the appropriate age curve look-up table (LUT) to use for age compensation using voltage ratios, according to one embodiment of the present invention.

DETAILED DESCRIPTION OF EMBODIMENTS

[0042] The Figures (FIG.) and the following description relate to preferred embodiments of the present invention by way of illustration only. It should be noted that from the following discussion, alternative embodiments of the structures and methods disclosed herein will be readily recognized as viable alternatives that may be employed without departing from the principles of the claimed invention.

[0043] Reference will now be made in detail to several embodiments of the present invention(s), examples of which are illustrated in the accompanying figures. It is noted that wherever practicable similar or like reference numbers may be used in the figures and may indicate similar or like functionality. The figures depict embodiments of the present invention for purposes of illustration only. One skilled in the art will readily recognize from the following description that alternative embodiments of the structures and methods illustrated herein may be employed without departing from the principles of the invention described herein.

[0044] FIG. 4A illustrates an active matrix OLED display according to one embodiment of the present invention, and FIG. 4B illustrates the age correction circuit shown in FIG. 4A in more detail according to one embodiment of the present invention. FIGS. 4A and 4B will be explained together. Referring to FIG. 4A, the AMOLED display 400 of FIG. 4A is substantially the same as the AMOLED display 100 of FIG. 1, except that a calibration engine 402, a selection look-up table (LUT) 404, and an age correction circuit 408 are added. The age correction circuit 408 receives the standard DN 101, row timing data 110, and column timing data 106, and generates a corrected DN 410 compensating for error introduced by aging of the OLED sub-pixels for output to gamma network 104.

[0045] Referring to FIG. 4B, age correction circuit 408 includes correction LUT 456, curve selector 458, age curve LUTs 460-1, 460-2, 460-3, . . . , 460-*n*, and adder (summing function) 470. Age curve LUTs 460 store the DN level increase (or decrease) Δ DN relative to the standard DN 101 that is needed to force the aged OLED sub-pixels to display the desired brightness as represented by the standard DN 101. In other words, age curve LUTs 460 store mappings from standard DN 101 to Δ DN 472. Methods of determining the age curve content to store in the age curve LUTs 460 are described below with reference to FIGS. 7A and 7B. Each sub-pixel 120 (or pixel) is assigned to one of the age curve LUTs 460 for age correction. Correction LUT 456 stores the mapping between the sub-pixel number and one of the age curve LUTs 460 to use for that sub-pixel number, during normal operation.

[0046] Referring to both FIGS. 4A and 4B, during manufacturing or testing of an AMOLED display, voltage ratios or current ratios from the OLED sub-pixels 120 may be measured 414, as explained in more detail below with reference to FIGS. 7A and 7B, to determine the age of the OLED of the sub-pixel and obtain light emission characteristics of aged sub-pixels for different ages of the sub-pixels. Such determined light emission characteristics of the aged sub-pixels for different ages may be stored in each of the age curve LUTs 460 for each age, as mappings between a standard DN 101 and a correction (Δ DN) 472 (increase or decrease) to the standard DN 101 that needs to be made for that age of the sub-pixel. Mappings between a particular age of an OLED sub-pixel and a particular age curve LUT 460 to use for that age are stored in selection LUT 404. The process of filling the content in the age curve LUTs 460 and selection LUT 404 may be completed during manufacturing or testing of the AMOLED display, before the AMOLED displays are put in actual use.

[0047] Referring to both FIGS. 4A and 4B, after the OLED display has been in actual use and during a calibration phase of the AMOLED display, calibration engine 402 determines the age of the aged sub-pixel 120 using voltage ratio or current ratio as explained in more detail with reference to FIGS. 9A and 9B, and then determines the age curve LUT 460 to use for that aged sub-pixel by looking up the selection LUT 404. Then, calibration engine 402 updates 412 correction LUT 456 based on the determined age of the aged sub-pixel, so that the particular aged sub-pixel being calibrated is assigned to the proper age curve LUT 460 for that determined age. Calibration phase can occur, for example, while the electronic device (e.g., mobile phone) in which the OLED display is used is not in normal operation (e.g., in charge mode of the mobile phone).

[0048] In normal operation, the standard DN 101 for a sub-pixel 120 is corrected by the age correction circuit 408 to a corrected DN value 410, which is input to the gamma network 104 to drive the T1 gate voltage 102. This is explained in more detail in FIG. 4B. Correction LUT 456 receives row timing data 105 and column timing data 106 that include the row and column numbers to be driven, respectively, from timing controller 112, and determines which pixel (sub-pixel) is to be driven by the graphics controller (not shown). As explained above, correction LUT 456 stores mappings between the sub-pixel numbers (identified by row number 105 and column number 106) and the number of the assigned age curve LUT 460 to use for that sub-pixel, as a result of calibration of the aged pixels by calibration engine

402 as explained above and below in more detail with reference to FIGS. 9A and 9B. Correction LUT 456 receives the row number 105 and the column number 106 of the sub-pixel of the OLED display that is currently being driven, and selects and outputs the age curve LUT number 457 to use for that sub-pixel. Curve selector 458 is essentially a decoder, and receives the selected curve number 457 and selects the corresponding one of the age curve LUTs 460-1, 460-2 . . . , 460-*n* to be used based on the selected curve number 457. For example, the selected age curve LUT number 457 may indicate that age curve LUT No. 3 460-3 should be used for the sub-pixel currently being driven, in which case curve selector 458 selects age curve LUT No. 3 (460-3).

[0049] Meanwhile, the standard DN 101 output from timing controller 112 is input to curve selector 458 and adder 470. The selected age curve LUT no. 3 (460-3) selects the correction Δ DN (increase or decrease) needed to be made to the standard DN 101 to compensate for aging of the OLED material of the OLED sub-pixel, based on the received standard DN 101. The correction Δ DN 472 is added to the standard DN 101 by adder (summing function) 470 to generate the corrected DN 410. The corrected DN 410 is one that has been compensated for aging of the OLED sub-pixel, and is provided to gamma network 104 to drive the T1 gate voltage 102 of the aged OLED sub-pixel.

[0050] Note that in another embodiment, age curve LUTs 460 may store mappings between the standard DN 101 representing the desired pixel brightness and the actual corrected DN 410 that is required to force the aged OLED sub-pixels corresponding to that particular aged pixel to emit the desired brightness, rather than the correction Δ DN (increase or decrease) needed to be made to the DN 101. In such an embodiment, no adder is needed since the age curve LUTs 460 outputs the corrected DN 410 itself. However, in such embodiment more memory space would be needed to store the longer bits of the actual corrected DN 410.

[0051] The number of age curve LUTs needed for age compensation in the OLED display depends on the desired age resolution of the OLED display, i.e., the granularity of the age compensation desired. In one embodiment, when the OLED light emission efficiency has decreased to 50% of its un-aged efficiency, the OLED is deemed to have reached the end of its life. Assuming a 6-bit system is used to store the age curve LUT numbers, 50% divided by 64 ($=2^6$) results in 0.78% efficiency difference between adjacent age curves. For an OLED material that has a half-life of 20,000 hours, there would be an age curve spaced approximately every 312 hours ($=20,000/64$). Each of the 64 age curve LUTs would be associated with a particular age for which it contains DN correction data.

[0052] FIGS. 5A and 5B illustrate a sub-pixel of the AMOLED display in more detail. As shown in FIG. 5A, TFT T1 and OLED D1 are connected in series between supply voltages Vdd and Vss. The same current I_{oled} flows through both TFT T1 and OLED D1. When TFT T1 is biased in the saturation region, $I_d = k \cdot (V_{gs} - V_t)^2$ (Equation 1) holds, where V_{gs} is the voltage between the gate and source of TFT T1, V_t is the threshold voltage of T1, V_{ds} is the voltage from drain to source of TFT T1, I_d is the current through TFT T1, and k is a proportionality constant reflecting electron mobility of TFT T1. Thus, the magnitude of the current I_{oled} (current I_d) when T1 is biased in the saturated region is controlled by the gate voltage on TFT T1. When TFT T1 is biased in the linear region, $I_d = 2k[(V_{gs} - V_t) \cdot V_{ds} - V_{ds}^2/2]$ (Equation 2) holds. If

TFT T1 is biased in the linear region and its gate voltage is fixed, the current is controlled by its drain-source voltage Vd across T1. In addition, $V_{total} = V_{dd} - V_{ss}$ (Equation 3) and $V_{total} = V_{ds} + V_{oled}$ (Equation 4), where Vtotal is the total voltage across TFT T1 and OLED D1, Vdd is the power supply voltage, Vd is the voltage across TFT T1, Voled is the voltage across OLED D1, and Vss is ground voltage (typically 0 volt).

[0053] If TFT T1 is placed in the linear mode by connecting the gate of TFT T1 to the cathode of OLED D1 as shown in FIG. 5B, the current Ioled is a function of the Voled and Vtotal. But since Ioled is also a function of Ioled, Ioled cannot be found by just knowing Vtotal, which is the only voltage that can be directly measured. Knowing the threshold voltage Vt and k of TFT T1, current measurement of Ioled will allow the calculation of Vds from Equation 2, which can then be subtracted from Vtotal to obtain Voled. If a specific voltage Vtotal is applied to the sub-pixel 120, the sub-pixel circuit will settle to a current Ioled as a function of Vdd, Vss. Therefore, if two sub-pixels have the same Vdd and Vss and their gates are connected to the cathodes to put the OLEDs D1 in linear mode, then the current Ioled in the two sub-pixels should be identical, assuming that the TFTs T1 and OLED D1s in the two sub-pixels are identical. The TFT T1s in the two sub-pixels are assumed to be stable and both sub-pixels are assumed to be at the same temperature. If one sub-pixel is aged but another sub-pixel is not aged and identical Vdd and Vss are applied to both the aged sub-pixel and the un-aged sub-pixel (referred to herein as the "reference sub-pixel"), the current Ioled in the reference sub-pixel will be different from the current Ioled in the aged sub-pixel, i.e., the OLED current Ip in the aged sub-pixel will be less than the OLED current Ir in the reference sub-pixel. Stated in another way, larger Vtotal (Vdd-Vss) needs to be applied to the aged sub-pixel than to the reference sub-pixel to obtain the same current Ioled in the aged sub-pixel and the reference sub-pixel, due to the aged OLED D1 in the aged sub-pixel. These properties may be used to determine the age of a sub-pixel.

[0054] FIG. 6 illustrates how an AMOLED display is aged, according to one embodiment of the present invention. For example, aging of the AMOLED display is carried out as in FIG. 6 in the laboratory during characterization of the OLED production process, in order to determine the proper correction needed to be made to the DNs in the AMOLED displays put into actual use and aged. The active area 600 of the AMOLED test display is divided into a plurality of sections each of which is aged differently and at least one section with reference pixels that are not aged. For example, active area 600 includes 16 sections 602, 604, . . . , 630 and a reference pixel section 632. Each of the sixteen sections 602, 604, . . . , 632 contains thousands of pixels, and is aged by having current flow through its sub-pixels for a predetermined period of time, but with each section having different amounts of current flowing through its sub-pixels in order to produce sixteen different rates of aging. For example, section 602 is aged for 250 hours at a predetermined current level, say 1A. Section 604 is aged for 250 hours but at twice the predetermined current level (2-1A) that produces a two to one aging acceleration and thus is effectively aged 500 hours. The current levels are increased in a similarly manner to 3-1A, 4-1A, . . . , 16-1A for sections 606, 608, . . . , 632, respectively, until the sixteenth section 632 is aged at a 16 to 1 rate to produce a section of pixels that have an effective age of 4000 hours. After aging is completed in this manner, the display has pixels

ranging from 250 hours to 4000 hours in effective age. The reference pixels 632 remain un-aged.

[0055] FIG. 7A illustrates a method of determining corrected digital numbers (DNs) to use with aged sub-pixels of an AMOLED display using current ratios, according to one embodiment of the present invention. According to the method of FIG. 7A, a predetermined reference voltage is applied to the OLED sub-pixels in differently aged sections of the aged OLED 600 (FIG. 6) and the resulting current and light emission in the OLED sub-pixels are measured. As the OLED display ages, current through the OLEDs will decrease and the current to light efficiency will also decrease. Therefore, the current decrease is a measure of decrease in OLED efficiency, from which a correction to DN may be deduced. An assumption in the method of FIG. 7A is that the efficiency change in the OLED is due to aging and not some other ambient parameter, which is true in many practical instances.

[0056] More specifically, at step 702 the sections of the OLED panel are aged, for example, according to the method illustrated with reference to FIG. 6. Then, at step 704 same supply voltages Vdd and Vss (see FIGS. 5A and 5B) are applied to the aged sub-pixels in one ages section (602, 604, . . . , or 630) and to the reference sub-pixels (un-aged sub-pixels) in un-aged section 632, and in step 706 the currents through one or more of the aged sub-pixels and the currents through one or more of the reference sub-pixels are measured and averaged to determine the average sub-pixel current (Ip) in the selected aged section (602, 604, . . . , or 630) and the average sub-pixel current (Ir) in the un-aged section 632. One way of measuring the sub-pixel current of an OLED display is taught in U.S. patent application Ser. No. 11/710,462, filed by Walter Edward Naugler, Jr., et al. on Feb. 22, 2007 and entitled "Method and Apparatus for Managing and Uniformly Maintaining Pixel Circuitry in a Flat Panel Display," which is incorporated by reference herein. Another way of measuring sub-pixel current of an OLED display is taught in U.S. patent application Ser. No. 12/018,455 filed by Walter Edward Naugler, Jr., et al. on Jan. 23, 2008 and entitled "Sub-Pixel Current Measurement for OLED Display," which is incorporated by reference herein. Other conventional methods of measuring the sub-pixel current of an OLED display may be used with embodiments of the present invention. Note that the current driving TFT T1 should be separated from the operation of the OLED D1 when current is measured, which can be accomplished by tying the gate of TFT T1 to the supply voltage Vss that is also coupled to the cathode of OLED D1 to place the TFT T1 in linear mode. Supply voltage Vdd is chosen to be small enough not to cause local heating in the sub-pixels. In measuring sub-pixel current in step 706, all other pixels are turned off by applying a gate voltage 120 to the gates of the TFTs T1 calculated to switch each sub-pixel off with minimum dark current. One way of switching OLED sub-pixels off to achieve minimum dark current is taught in U.S. patent application Ser. No. 12/033,527, filed by Walter Edward Naugler, Jr. on Feb. 19, 2008 and entitled "Minimizing Dark Current in OLED Display Using Modified Gamma Network," which is incorporated by reference herein. Other conventional methods of reducing dark current may be used with embodiments of the present invention.

[0057] At step 708, the current ratio (Ip/Ir) corresponding to the aged sub-pixel is determined. For fixed supply voltages Vdd and Vss, the current ratio (Ip/Ir) will be less than 1 as the aged sub-pixels have less efficiency. The amount of current ratio (Ip/Ir) less than 1 indicates the age of the pixel. Since it

is known which section of the OLED panel the measured aged sub-pixel belongs to, the determined current ratio (I_p/I_r) is a measure of the effective age of the aged sub-pixel and the current ratio (I_p/I_r) and the age can be mapped. Thus, at step **708** the selection LUT **404** is also updated to reflect a proper mapping between the effective age (represented by the current ratio (I_p/I_r)) of the aged sub-pixel and an age curve LUT number corresponding to the effective age represented by the current ratio. Current from the aged sections and the current ratio (I_p/I_r) will steadily become smaller as the current measurement moves from the 250 hour-aged section **602** to the 4000 hour-aged section **632**.

[0058] At step **710**, light emission characteristics in the aged sub-pixel are determined. Specifically, at step **710** the light emission (brightness in candela) of the aged sub-pixel for given DNs is measured for a particular age of the OLED represented as the current ratio (I_p/I_r).

[0059] At step **712**, such light emission characteristics are used to determine the corrected digital number needed to achieve a particular brightness of an aged sub-pixel. FIG. **8** illustrates the relationship between OLED brightness and digital numbers (DNs) for different ages of the OLEDs, according to one embodiment of the present invention. For example, the three curves **852**, **854**, **856** show the brightness vs. digital number relationship for three different pixel ages **A1**, **A2**, and **A3**, respectively. The data for the graph in FIG. **8** may be obtained from the age test using the test display shown in FIG. **6**, assuming that the laboratory test display in FIG. **6** is identical in design and production process as the OLED display units sent into the field for actual customer usage. Since the test display of FIG. **6** is also an actual display, the OLED display may be turned on by supplying a DN gray level to the pixels using a graphics board (not shown) and the pixel brightness may be measured, in order to obtain the DN data on the x-axis and the brightness data on the y-axis. The brightness of the pixels may be measured in candelas using an optical photometer.

[0060] From the graph in FIG. **8** it is possible to determine the digital number (DN) needed to achieve a certain brightness in the OLED for different ages of the OLED sub-pixels. For example, curves **852**, **854**, **856** represent the relations between DN and achieved brightness for sub-pixels aged **A1**, **A2**, **A3**, respectively, with **A3** being the most aged, followed by **A2**, and **A1** being the least aged. In order to achieve a brightness of **B1**, sub-pixel aged **A1** (curve **852**) requires DN of 150, sub-pixel aged **A2** (curve **854**) requires DN of 200, and sub-pixel aged **A3** (curve **856**) requires DN of approximately 230. If sub-pixel aged **A1** is the reference sub-pixel, sub-pixel aged **A2** requires DN correction (Δ DN) of +50 for standard DN of 150, and sub-pixel aged **A3** requires DN correction (Δ DN) of +80 for standard DN. Thus, at step **712** such DN correction data with respect to a standard DN **150** is also stored in each of the age curve LUTs **460** corresponding to the age (**A2**, **A3**) of the sub-pixel.

[0061] Steps **704**, **706**, . . . , **712** are repeated, moving from one aged section (**602**, **604**, . . . , **630**) to another aged section (**602**, **604**, . . . , **630**) in step **716**, until the last aged sub-pixel section is reached in step **714** and the process ends **718**. Note that the method of FIG. **7A** is most effective if (i) the TFTs in the AMOLED display are stable, (ii) the reference pixels are stable and remain in the initial state over the lifetime of the display, (iii) the temperature of the OLED display is uniform during measurement of the current, (iv) the test currents used do not appreciably increase the temperature, (v) the test dis-

plays are from a stable production process, and (vi) the gamma networks **104** in the test display of FIG. **6** are same as those that would be included in OLED displays that are put in actual use in the field.

[0062] FIG. **7B** illustrates a method of determining corrected digital numbers (DNs) to use with aged sub-pixels of an AMOLED display using voltage ratios, according to one embodiment of the present invention. According to the method of FIG. **7B**, a predetermined reference current is applied to the OLED sub-pixels to differently aged sections of the aged OLED display **600** (FIG. **6**) and the voltage ($V_{total}=V_{dd}-V_{ss}$ in FIGS. **5A** and **5B**) across the OLED sub-pixel and light emission in the OLED sub-pixels are measured. In one embodiment, the OLED sub-pixel may be forced to have the reference current flow using conventional feedback circuits (not shown herein). If V_{ss} is fixed (e.g., at ground), V_{total} can be measured by measuring V_{dd} . As the OLED ages, the voltage ($V_{total}=V_{dd}-V_{ss}$) required to have the reference current flow through the OLEDs will increase. Therefore, the voltage increase is a measure of decrease in the OLED efficiency, from which a correction to DN may be deduced. An assumption in the method of FIG. **7B** is that the efficiency change in the OLED is due to aging and not some other ambient parameter, which is true in many practical instances.

[0063] More specifically, at step **752** the sections of the OLED panel are aged, for example, according to the method illustrated with reference to FIG. **6**. Then, at step **754** the average supply voltage V_{dd} (referred to as V_r) (with V_{ss} fixed) needed to force the predetermined reference current in one or more of the reference sub-pixels in the reference pixel section **632** is determined. Also, at step **756**, the average supply voltage V_{dd} (referred to as V_p) (with V_{ss} fixed) needed to force the predetermined reference current in one or more of the aged sub-pixels in the aged pixel section (**602**, **604**, . . . , **630**) is determined.

[0064] At step **758**, the voltage ratio (V_p/V_r) corresponding to the aged sub-pixels is determined. For fixed reference current and fixed V_{ss} , the voltage ratio (V_p/V_r) will be greater than 1 as the aged sub-pixels have less efficiency. The amount of voltage ratio (V_p/V_r) greater than 1 indicates the age of the pixel. Since it is known which section of the OLED panel the measured aged sub-pixels belong to, the determined voltage ratio (V_p/V_r) is a measure of the effective age of the measured sub-pixels and the voltage ratio (V_p/V_r) and the age can be mapped. Thus, at step **758** the selection LUT **404** is also updated to reflect a proper mapping between the effective age (represented by voltage ratio) of the aged sub-pixels and an age curve LUT number corresponding to the effective age represented by the voltage ratio. The voltage V_p needed for the aged sections and the voltage ratio (V_p/V_r) will steadily become larger as the voltage measurement moves from the 250 hour-aged section **602** to the 4000 hour-aged section **632**.

[0065] At step **760**, light emission characteristics in the aged sub-pixel are determined. Specifically, at step **760** light emission (brightness in candela) of the aged sub-pixel for given DNs is determined. At step **762**, such light emission characteristics are used to determine the corrected digital number needed to achieve a particular brightness of an aged sub-pixel, similar to the embodiment of FIG. **7A**, and such DN correction data with respect to a standard DN is also stored in each of the age curve LUTs **460** corresponding to the age of the sub-pixel.

[0066] The process of steps 754, 756, . . . , 762 are repeated, moving from one aged section (602, 604, . . . , 630) to another aged section (602, 604, . . . , 630) in step 766, until the last aged sub-pixel section is reached in step 764 and the process ends 768. Note that the method of FIG. 7B is also most effective if (i) the TFTs in the AMOLED display are stable, (ii) the reference pixels are stable and remain in the initial state over the lifetime of the display, (iii) the temperature of the OLED display is uniform during measurement of the current, (iv) the test currents used do not appreciably increase the temperature, (v) the test displays are from a stable production process, and (vi) the gamma networks 104 in the test display of FIG. 6 are same as those that would be included in OLED displays that are put in actual use in the field.

[0067] A possible advantage of using the voltage ratio embodiment of FIG. 7B over the current ratio embodiment of FIG. 7A is that the same current is forced through the reference pixels and aged pixels. The change in the supply voltage in the voltage ratio embodiment of FIG. 7B is caused only by an increase in the OLED voltage, V_{oled} (see FIGS. 5A and 5B). On the other hand, the current change in the current ratio embodiment of FIG. 7A is caused by changes in both the OLED voltage (V_{oled}) and the OLED current (I_{oled}), which may slightly reduce the accuracy of the current ratio embodiment of FIG. 7A.

[0068] FIG. 9A illustrates a method of determining the appropriate age curve look-up table (LUT) to use for age compensation using current ratios, according to one embodiment of the present invention. The method of FIG. 9A is used during calibration of the AMOLED display to determine how aged the OLED sub-pixels are and how to compensate for the reduced light efficiency of the aged OLED sub-pixels. The method of FIG. 9A may be performed by the calibration engine 402 (see FIG. 4A). The method of FIG. 9A is carried out with respect to an aged AMOLED display that has been in use for some time, and may be performed multiple times during the life of the AMOLED display, for example, periodically, or during inactive periods of the AMOLED display, etc. Note that the aged AMOLED display used with the methods of FIGS. 9A and 9B is one that has been in actual use and is separate from the test OLED panel 600 shown in FIG. 6 which was used to generate the age curve LUTs according to the methods described in FIGS. 7A and 7B. However, in one embodiment the actual panel in use may also include un-aged, un-used reference pixels similar to the reference pixels 632 in FIG. 6. Such reference pixels on the actual panel in use have minimal aging and are expected to stay in their pristine original state despite being accessed occasionally for calibration. In another embodiment the actual panel in use does not include un-aged, un-used reference pixels, but the methods of FIGS. 9A and 9B may use the youngest pixels in place of the reference pixels in such other embodiment.

[0069] At step 904, the same supply voltages V_{dd} and V_{ss} (see FIGS. 5A and 5B) are applied to one of the aged sub-pixels (e.g., sub-pixel at Row 1, Column 1) and to one of the reference sub-pixels (un-aged sub-pixels), and at step 906 the current (I_p) through the aged sub-pixel and the current (I_r) through the reference sub-pixel are measured. Note that alternatively the average current through many of the reference sub-pixels may be measured and averaged, for use in place of the referenced current (I_r) for one reference sub-pixel in step 906, in which case the reference current does not need to be measured every time step 906 is performed. The average reference current may be used instead. Reference current (I_r)

herein may refer to the current in one reference sub-pixel or the average reference current through a plurality of reference sub-pixels.

[0070] At step 908, the current ratio (I_p/I_r) corresponding to the aged sub-pixel is determined. As explained above, the determined current ratio (I_p/I_r) is a measure of the effective age of the measured sub-pixel. Thus, at step 910 calibration engine 402 looks up selection LUT 404 to select the proper age curve LUT number corresponding to the determined age of the aged sub-pixel based on the current ratio (I_p/I_r). At step 911 calibration engine 402 updates (412 in FIG. 4A) correction LUT 456 in the age correction circuit 408 to reflect the selected age curve LUT number for the aged sub-pixel. That way, in normal operation, standard DNs 101 for the aged sub-pixel will be corrected by the selected age curve LUT 460. The process of steps 904, 906, . . . , 911 are repeated, moving from sub-pixel to sub-pixel in step 914, until the last aged sub-pixel is reached in step 912 and the process ends 914.

[0071] FIG. 9B illustrates a method of determining the appropriate age curve look-up table (LUT) to use for age compensation using voltage ratios, according to one embodiment of the present invention. The method of FIG. 9B may also be used during calibration of the AMOLED display to determine how aged the OLED sub-pixels are and how to compensate for the reduced light efficiency of the aged OLED sub-pixels. The method of FIG. 9B may be performed by the calibration engine 402 (see FIG. 4A). The method of FIG. 9B is thus carried out with respect to an aged AMOLED display that has been in use for some time, and may be performed multiple times during the life of the AMOLED display, for example, periodically, or during inactive periods of the AMOLED display, etc.

[0072] At step 954, a reference current is forced through one of the aged sub-pixels and the reference sub-pixels. At step 956 the average supply voltage V_{dd} (referred to as V_r) (with V_{ss} fixed) needed to force the predetermined reference current in the reference sub-pixels is determined. Also, at step 956, the supply voltage V_{dd} (referred to as V_p) (with V_{ss} fixed) needed to force the predetermined reference current in one of the aged sub-pixels (e.g., sub-pixel at Row 1, Column 1) is determined. At step 958, the voltage ratio (V_p/V_r) corresponding to the aged sub-pixel is determined. As explained above, the determined voltage ratio (V_p/V_r) is also a measure of the effective age of the measured sub-pixel. Thus, at step 960 calibration engine 402 looks up selection LUT 404 to select the proper age curve LUT number corresponding to the determined age of the aged sub-pixel based on the voltage ratio (V_p/V_r). At step 961 calibration engine 402 updates (412 in FIG. 4A) correction LUT 456 in the age correction circuit 408 to reflect the selected age curve LUT number for the aged sub-pixel. That way, in normal operation, standard DNs 101 for the aged sub-pixel will be corrected by the selected age curve LUT 460. The process of steps 954, 956, . . . , 961 are repeated, moving from sub-pixel to sub-pixel in step 964, until the last aged sub-pixel is reached in step 962 and the process ends 964.

[0073] According to the present invention, it is possible to conveniently determine the age of an aged sub-pixel relative to un-aged reference sub-pixels using voltage ratios or current ratios, and correlate such age measurement with the correction that needs to be made to the DNs in order to compensate for reduced light efficiency of the aged sub-pixels of the OLED display.

[0074] Upon reading this disclosure, those of skill in the art will appreciate still additional alternative structural and functional designs for correcting digital numbers in order to compensate for reduced light efficiency of the aged sub-pixels of the OLED display. For example, although various embodiments of the present invention are illustrated as using voltage ratios or current ratios, the age of the sub-pixels do not necessarily have to be determined using strictly ratios, and any comparison of the current or voltage in the aged sub-pixels relative to the current or voltage in un-aged reference sub-pixels may be used. For instance, differences rather than ratios may be used. Thus, while particular embodiments and applications of the present invention have been illustrated and described, it is to be understood that the invention is not limited to the precise construction and components disclosed herein and that various modifications, changes and variations which will be apparent to those skilled in the art may be made in the arrangement, operation and details of the method and apparatus of the present invention disclosed herein without departing from the spirit and scope of the invention as defined in the appended claims.

What is claimed is:

1. A method of determining compensation needed for reduced light efficiency in aged sub-pixels of an active matrix organic light-emitting diode (OLED) display, the method comprising:

- aging a plurality of sections of sub-pixels of a first active matrix OLED display, the sections including at least a first section including aged sub-pixels and a second section including reference sub-pixels that are not aged;
- applying a predetermined voltage across one or more of the aged sub-pixels and one or more of the reference sub-pixels;
- determining a first current through said one or more of the aged sub-pixels and a second current through said one or more of the reference sub-pixels;
- determining an age of said one or more of the aged sub-pixels based on the first current relative to the second current;
- determining light emission characteristics of said one or more of the aged sub-pixels; and
- determining corrections to be made to digital numbers indicative of desired brightness in said one or more of the aged sub-pixels based on mappings between the determined age and the determined light emission characteristics of said one or more of the aged sub-pixels.

2. The method of claim 1, wherein the plurality of sections of the sub-pixels are aged for a same predetermined period of time but with different amounts of current flowing through two or more of the sections of the sub-pixels to obtain different effective ages in said two or more of the sections of the sub-pixels of the OLED display.

3. The method of claim 1, wherein determining the first current includes measuring the first current through two or more of the aged sub-pixels and averaging the measured first current, and determining the second current includes measuring the second current through two or more of the reference sub-pixels and averaging the measured second current.

4. The method of claim 1, wherein each of the sub-pixels of the active matrix OLED display include a thin film transistor configured to drive an OLED of the sub-pixel, and current through the aged sub-pixel or the reference sub-pixel is measured with the thin film transistor biased in linear mode.

5. The method of claim 1, wherein the age of said one or more of the aged sub-pixels is determined based on a current ratio of the first current to the second current, the current ratio being less than one and being smaller as the sub-pixels have longer effective age.

6. The method of claim 5, further comprising storing a mapping between the current ratio and the age of the aged sub-pixel in a selection look-up table.

7. The method of claim 1, further comprising storing said corrections to be made to the digital numbers in one of a plurality of age curve look-up tables corresponding to the determined age of the aged sub-pixel, each age curve look-up table corresponding to a different age of the aged sub-pixel and mapping the digital numbers to said corrections to be made to the digital numbers for the corresponding age of the aged sub-pixel, wherein one or more of the aged sub-pixels of the OLED display are assigned to use said one of the age curve look-up tables for correction of the digital numbers.

8. The method of claim 7, further comprising:

after a second active matrix OLED display is aged by actual use, applying the predetermined voltage across one of aged sub-pixels of the second active matrix OLED display and at least one of reference sub-pixels of the second active matrix OLED display;

determining a third current through said one of the aged sub-pixels of the second active matrix OLED display and a fourth current through said at least one of the reference sub-pixels of the second active matrix OLED display;

determining an age of said one of the aged sub-pixels of the second active matrix OLED display based on the third current relative to the fourth current;

selecting one of the age curve look-up tables to use for correction of the digital numbers indicative of desired brightness in said one of the aged sub-pixels of the second active matrix OLED display, based upon the determined age of said one of the aged sub-pixels of the second active matrix OLED display.

9. The method of claim 8, further comprising storing mappings between a sub-pixel number corresponding to said one of the aged sub-pixels of the second active matrix OLED display and an age curve look-up table number corresponding to the selected age curve look-up table in a correction look-up table.

10. A method of determining compensation needed for reduced light efficiency in aged sub-pixels of an active matrix organic light-emitting diode (OLED) display, the method comprising:

aging a plurality of sections of sub-pixels of a first active matrix OLED display, the sections including at least a first section including aged sub-pixels and a second section including reference sub-pixels that are not aged;

determining a first voltage applied to one or more of the aged sub-pixels to generate a predetermined reference current through said one or more of the aged sub-pixels;

determining a second voltage applied to one or more of the reference sub-pixels to generate the same predetermined reference current through said one or more of the reference sub-pixels;

determining an age of said one or more of the aged sub-pixels based on the first voltage relative to the second voltage;

determining light emission characteristics of said one or more of the aged sub-pixels;

determining corrections to be made to digital numbers indicative of desired brightness in said one or more of the aged sub-pixels based on mappings between the determined age and the determined light emission characteristics of said one or more of the aged sub-pixels.

11. The method of claim **10**, wherein the plurality of sections of the sub-pixels are aged for a same predetermined period of time but with different amounts of current flowing through two or more of the sections of the sub-pixels to obtain different effective ages in said two or more of the sections of the sub-pixels of the OLED display.

12. The method of claim **10**, wherein determining the first voltage includes measuring the first voltage across two or more of the aged sub-pixels with the same predetermined reference current flowing through said two or more of the aged sub-pixels and averaging the measured first voltage, and determining the second voltage includes measuring the second voltage across two or more of the reference sub-pixels with the same predetermined reference current flowing through said two or more of the reference sub-pixels and averaging the measured second voltage.

13. The method of claim **10**, wherein each of the sub-pixels of the active matrix OLED display include a thin film transistor configured to drive an OLED of the sub-pixel, and voltage across the aged sub-pixel or the reference sub-pixel is measured with the thin film transistor biased in linear mode.

14. The method of claim **10**, wherein the age of said one or more of the aged sub-pixels is determined based on a voltage ratio of the first voltage to the second voltage, the voltage ratio being greater than one and being larger as the sub-pixels have longer effective age.

15. The method of claim **15**, further comprising storing a mapping between the voltage ratio and the age of the aged sub-pixel in a selection look-up table.

16. The method of claim **10**, further comprising storing said corrections to be made to the digital numbers in one of a plurality of age curve look-up tables corresponding to the determined age of the aged sub-pixel, each age curve look-up table corresponding to a different age of the aged sub-pixel and mapping the digital numbers to said corrections to be made to the digital numbers for the corresponding age of the aged sub-pixel, wherein one or more of the aged sub-pixels of the OLED display are assigned to use said one of the age curve look-up tables for correction of the digital numbers.

17. The method of claim **16**, further comprising:

after a second active matrix OLED display is aged by actual use, determining a third voltage applied to one of aged sub-pixels of the second active matrix OLED display to generate the predetermined reference current through one of the aged sub-pixels of the second active matrix OLED display, and determining a fourth voltage applied to one or more of reference sub-pixels of the second active matrix OLED display to generate the same predetermined reference current through said one or more of the reference sub-pixels of the second active matrix OLED display;

determining an age of said one of the aged sub-pixels of the second active matrix OLED display based on the third voltage relative to the fourth voltage; and

selecting one of the age curve look-up tables to use for correction of the digital numbers indicative of desired brightness in said one of the aged sub-pixels of the second active matrix OLED display, based upon the

determined age of said one of the aged sub-pixels of the second active matrix OLED display.

18. The method of claim **17**, further comprising storing mappings between a sub-pixel number corresponding to said one of the aged sub-pixels of the second active matrix OLED display and an age curve look-up table number corresponding to the selected age curve look-up table in a correction look-up table.

19. An active matrix organic light-emitting diode (OLED) display comprising:

a plurality of OLED elements arranged in a plurality of rows and a plurality of columns, each of the OLED elements corresponding to a sub-pixel of the OLED display; and

an active matrix drive circuit configured to drive current through the OLED elements, the active matrix drive circuit including:

a plurality of age curve look-up tables each corresponding to a different age of aged sub-pixels of the OLED display and mapping digital numbers to corrections to be made to the digital numbers for the corresponding age of the aged sub-pixel, one or more of the aged sub-pixels of the OLED display being assigned to use said one of the age curve look-up tables for correction of the digital numbers;

a correction look-up table storing mappings between each of the OLED sub-pixels and said assigned one of the age curve look-up tables; and

a selection look-up table storing mappings between ages of the sub-pixels of the OLED display and the age curve look-up tables, the ages of the sub-pixels represented by current ratios or voltage ratios associated with the sub-pixels of the OLED display, and wherein the active matrix drive circuit is configured to receive the digital number indicative of a desired brightness of one of the aged sub-pixels and generate a corrected digital number for driving the OLED elements using the corrections to the digital numbers stored in the age curve look-up table assigned to said one of the aged sub-pixels.

20. The active matrix organic light-emitting diode (OLED) display of claim **19**, wherein the active matrix drive circuit further comprises a calibration engine configured to:

apply a predetermined voltage across said one of the aged sub-pixels and at least one of the reference sub-pixels;

determine a first current through said one of the aged sub-pixels and a second current through said at least one of the reference sub-pixels;

determine an age of said one of the aged sub-pixels based on the first current relative to the second current; and

select one of the age curve look-up tables to use for correction of the digital numbers in said one of the aged sub-pixels for storage in the correction look-up table, based upon the determined age of said one of the aged sub-pixels.

21. The active matrix organic light-emitting diode (OLED) display of claim **19**, wherein the active matrix drive circuit further comprises a calibration engine configured to:

determine a first voltage applied to said one of the aged sub-pixels to generate a predetermined reference current through said one of the aged sub-pixels, and determine a second voltage applied to one or more of reference sub-

pixels that are un-aged to generate the same predetermined reference current through said one or more of the reference sub-pixels;
determine an age of said one of the aged sub-pixels based on the first voltage relative to the second voltage; and
select one of the age curve look-up tables to use for correction to the digital numbers in said one of the aged sub-pixel for storage in the correction look-up table, based upon the determined age of said one of the aged sub-pixels.

22. The active matrix organic light-emitting diode (OLED) display of claim **19**, wherein the age curve look-up tables store mappings between the digital numbers and increases or decreases to be made to the digital numbers.

23. The active matrix organic light-emitting diode (OLED) display of claim **19**, wherein the age curve look-up tables store mappings between the digital numbers and corrected digital numbers.

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专利名称(译)	使用电压比或电流比的老化有源矩阵OLED显示器中的发射控制		
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申请(专利权)人(译)	立迪思科技股份有限公司.		
当前申请(专利权)人(译)	立迪思科技股份有限公司.		
[标]发明人	NAUGLER WALTER EDWARD BIDERMANN WILLIAM ROBERT		
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摘要(译)

使用相对于未老化的老化子像素的电流比或电压比来确定有源矩阵有机发光二极管 (OLED) 显示器的老化子像素中的光效率降低所需的补偿, 参考子像素。

