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(54) ORGANIC LIGHT-EMITTING DIODE (OLED) PRE-CHARGE CIRCUIT FOR USE IN A COMMON ANODE LARGE-SCREEN DISPLAY

(75) Inventors: **Gino Tanghe**, Merkem (BE); **Robbie Thielemanns**, Nazareth (BE)

(73) Assignee: **Barco NV**, Kortrijk (BE)

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(58) **Field of Classification Search** 345/76–83; 315/169.3; G09G 3/30, 3/32
See application file for complete search history.

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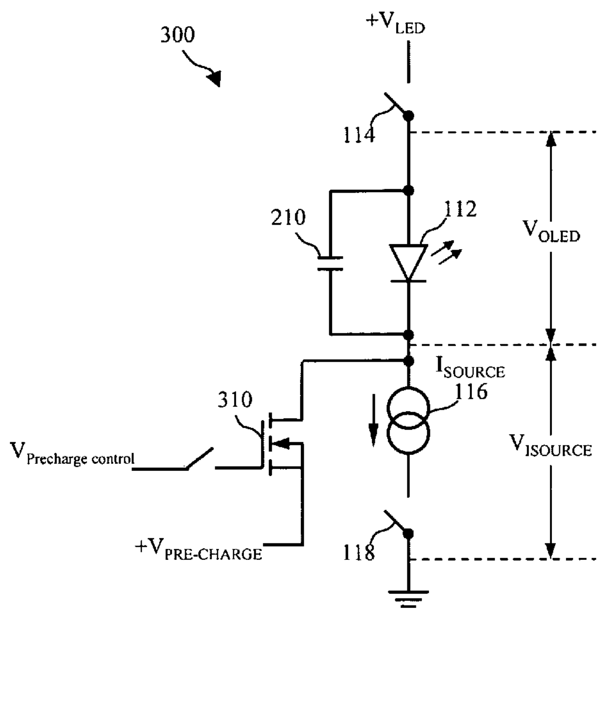
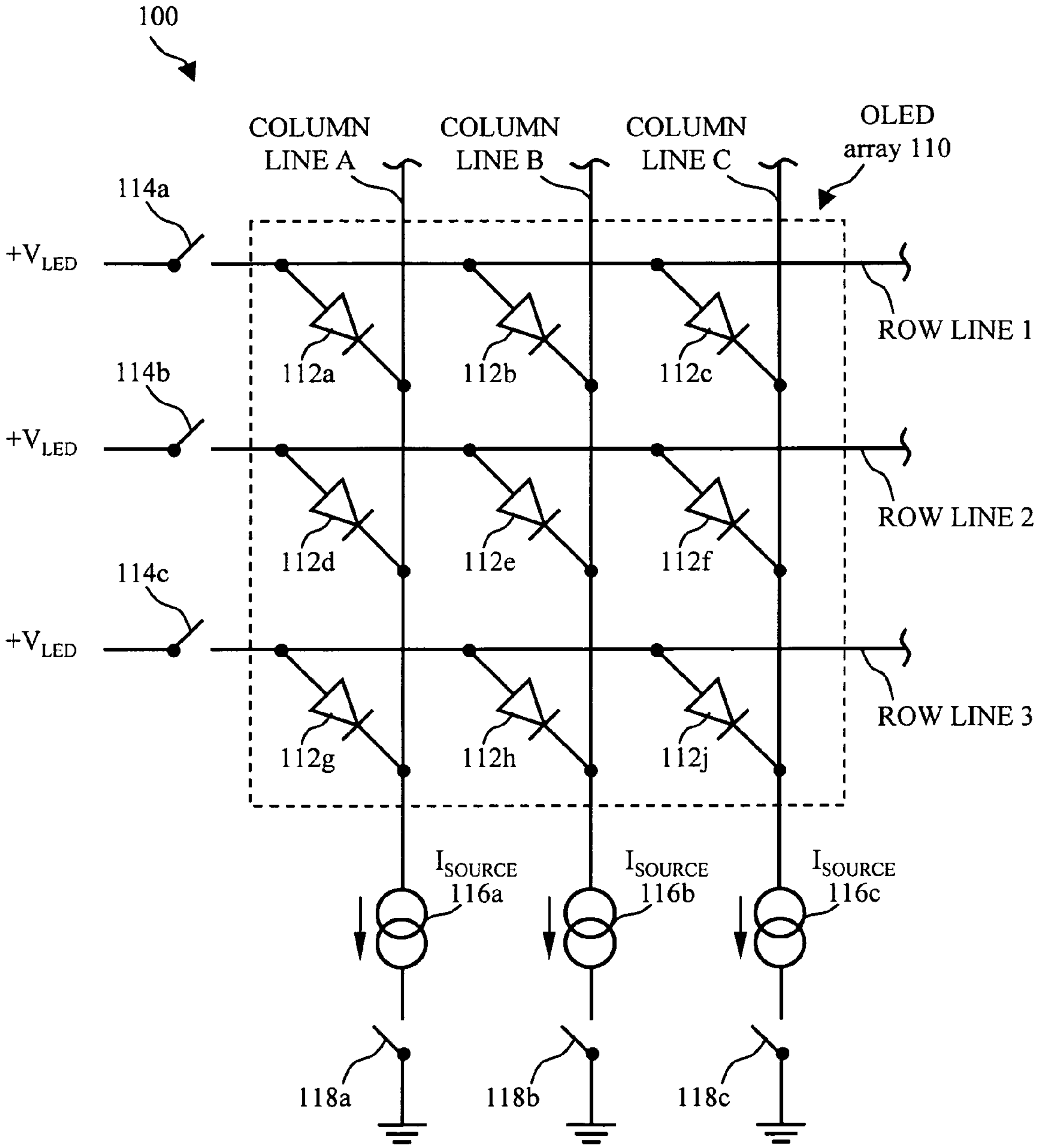
Primary Examiner—Alexander Eisen
(74) *Attorney, Agent, or Firm*—Barnes & ThornburgLLP

(57) **ABSTRACT**

The present invention is a pre-charge circuit integrated within the drive circuitry of a common anode, passive matrix, large-screen organic light-emitting diode (OLED) display device for overcoming the inherent capacitance characteristics C_{OLED} of the OLED devices therein. More specifically, a first pre-charge circuit of the present invention includes a MOSFET device integrated within the normal drive circuitry for applying a pre-charge voltage to the cathode of a given OLED device just prior to the desired "on" time, thereby overcoming C_{OLED} rapidly. A second pre-charge circuit of the present invention integrates within the normal drive circuitry a method of connecting the anode of a given OLED device to a positive voltage while concurrently connecting the cathode to ground just prior to the desired on time, thereby overcoming C_{OLED} rapidly. A third pre-charge circuit of the present invention includes an additional current source for supplying current over and above the normal operating current, which is activated just prior to the desired on time, thereby overcoming C_{OLED} rapidly. Finally, in a fourth pre-charge circuit of the present invention, a single current source is used that supplies a high current value just prior to the desired on time. Once the capacitor is charged, the output of this current source rapidly drops to the normal constant operating current.

21 Claims, 6 Drawing Sheets





100
COLUMN LINE A
COLUMN LINE B
COLUMN LINE C
OLED array 110
114a
114b
114c
$+V_{LED}$
$+V_{LED}$
$+V_{LED}$
112a
112b
112c
112d
112e
112f
112g
112h
112j
ROW LINE 1
ROW LINE 2
ROW LINE 3
I_{SOURCE} 116a
I_{SOURCE} 116b
I_{SOURCE} 116c
118a
118b
118c

Fig. 1

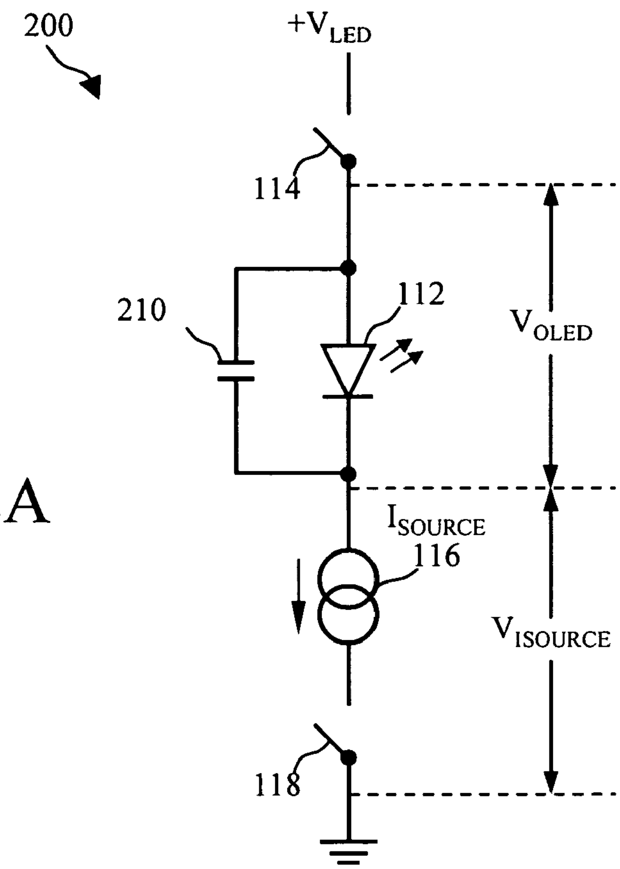

200
+V LED
114
210
112
V OLED
I SOURCE
116
V ISOURCE
118

Fig. 2A

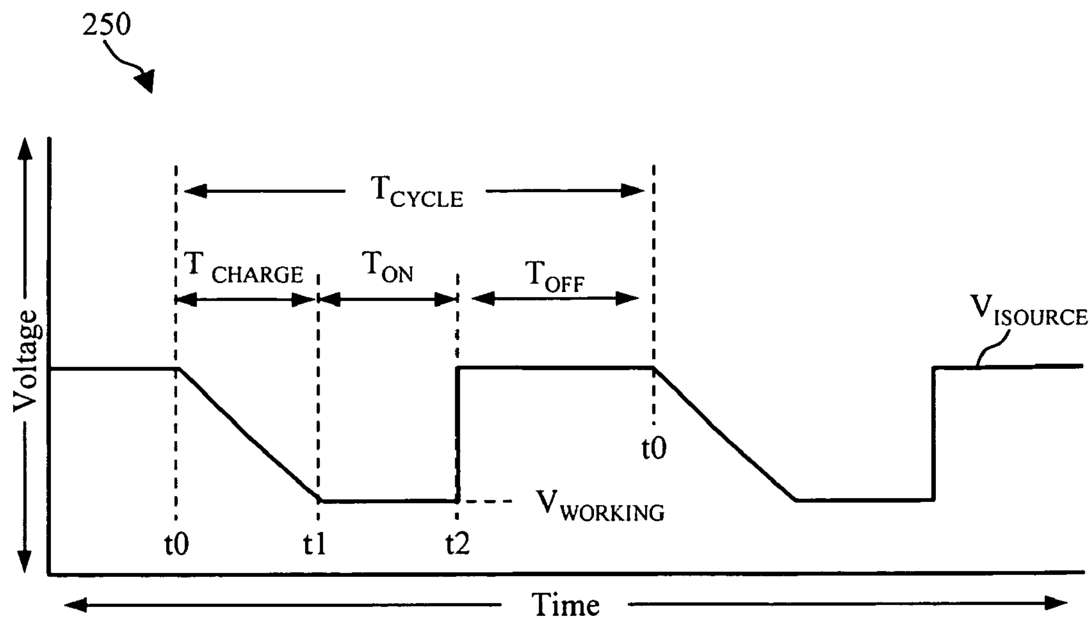

250
T CYCLE
T CHARGE
T ON
T OFF
V ISOURCE
Voltage
t0
V WORKING
t0
t1
t2
Time

Fig. 2B

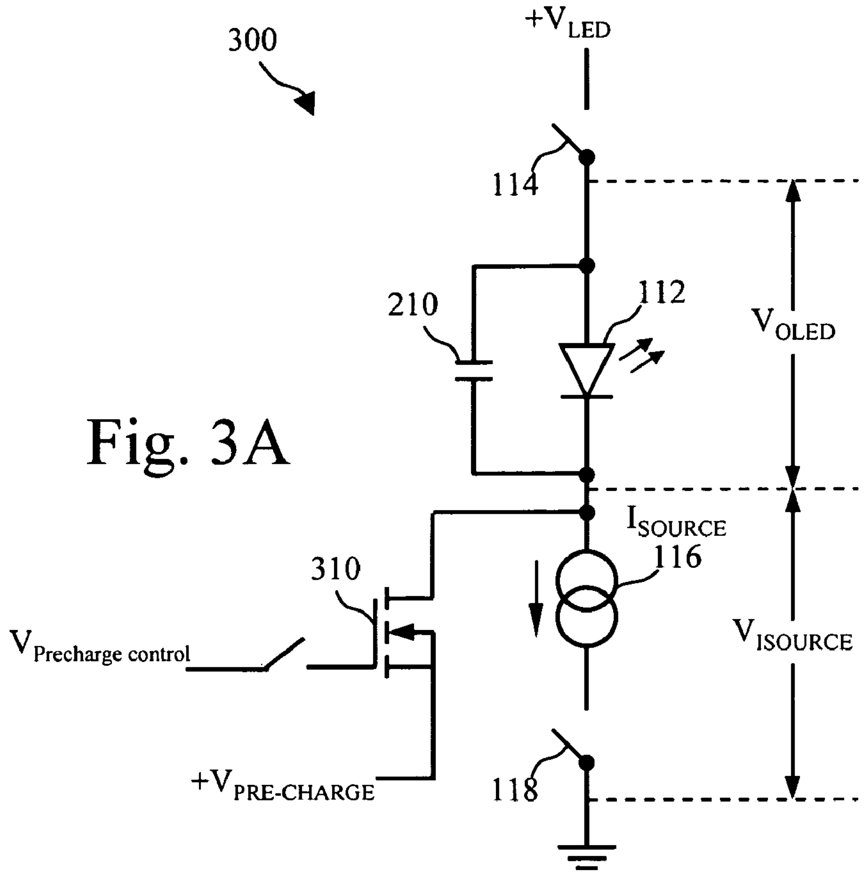

300
+V LED
114
210
112
V OLED
I SOURCE
116
310
V Precharge control
V ISOURCE
+V PRE-CHARGE
118

Fig. 3A

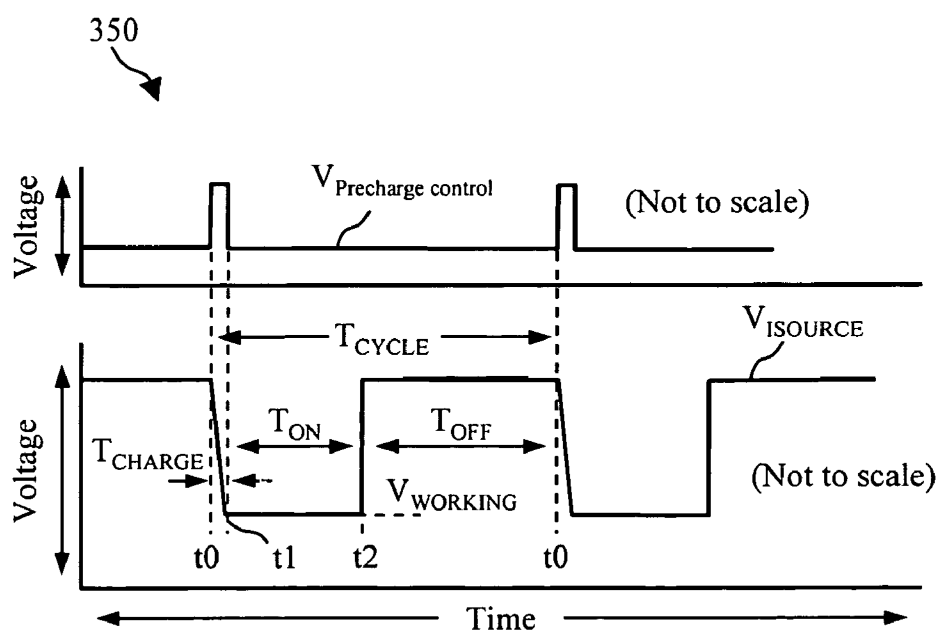
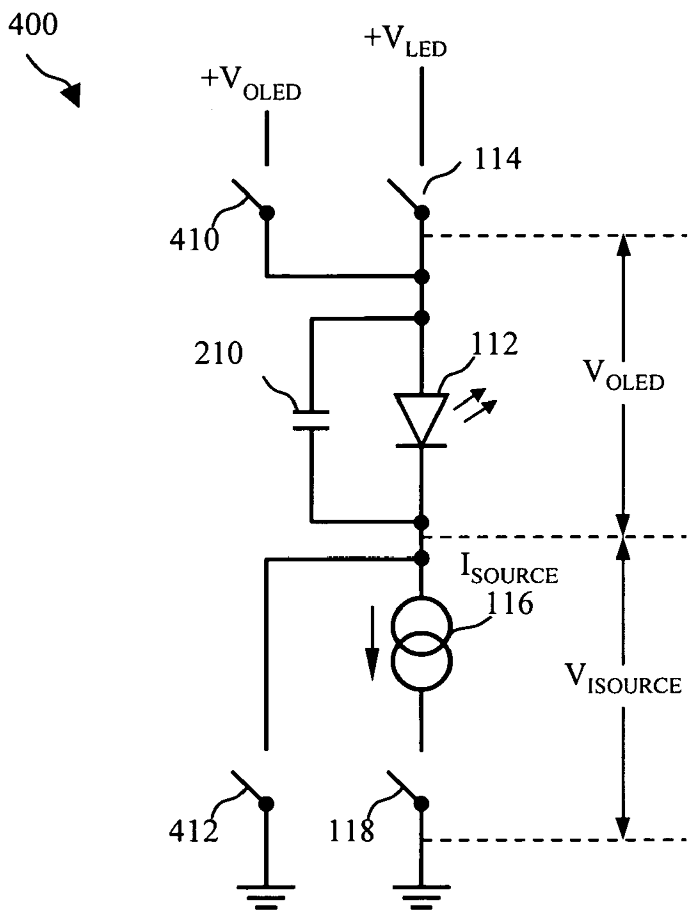

350
Voltage
V Precharge control
(Not to scale)
T CYCLE
V ISOURCE
Voltage
T CHARGE
T ON
T OFF
V WORKING
(Not to scale)
t0
t1
t2
t0
Time

Fig. 3B



400
$+V_{OLED}$
$+V_{LED}$
114
410
210
112
V_{OLED}
I_{SOURCE}
116
$V_{ISOURCE}$
412
118

Fig. 4

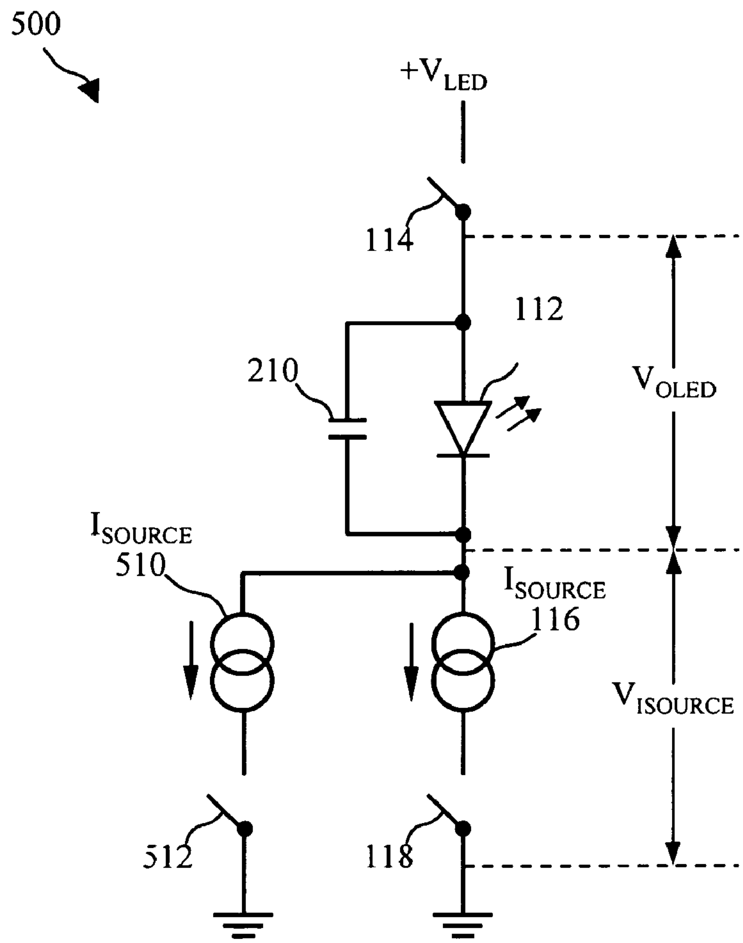
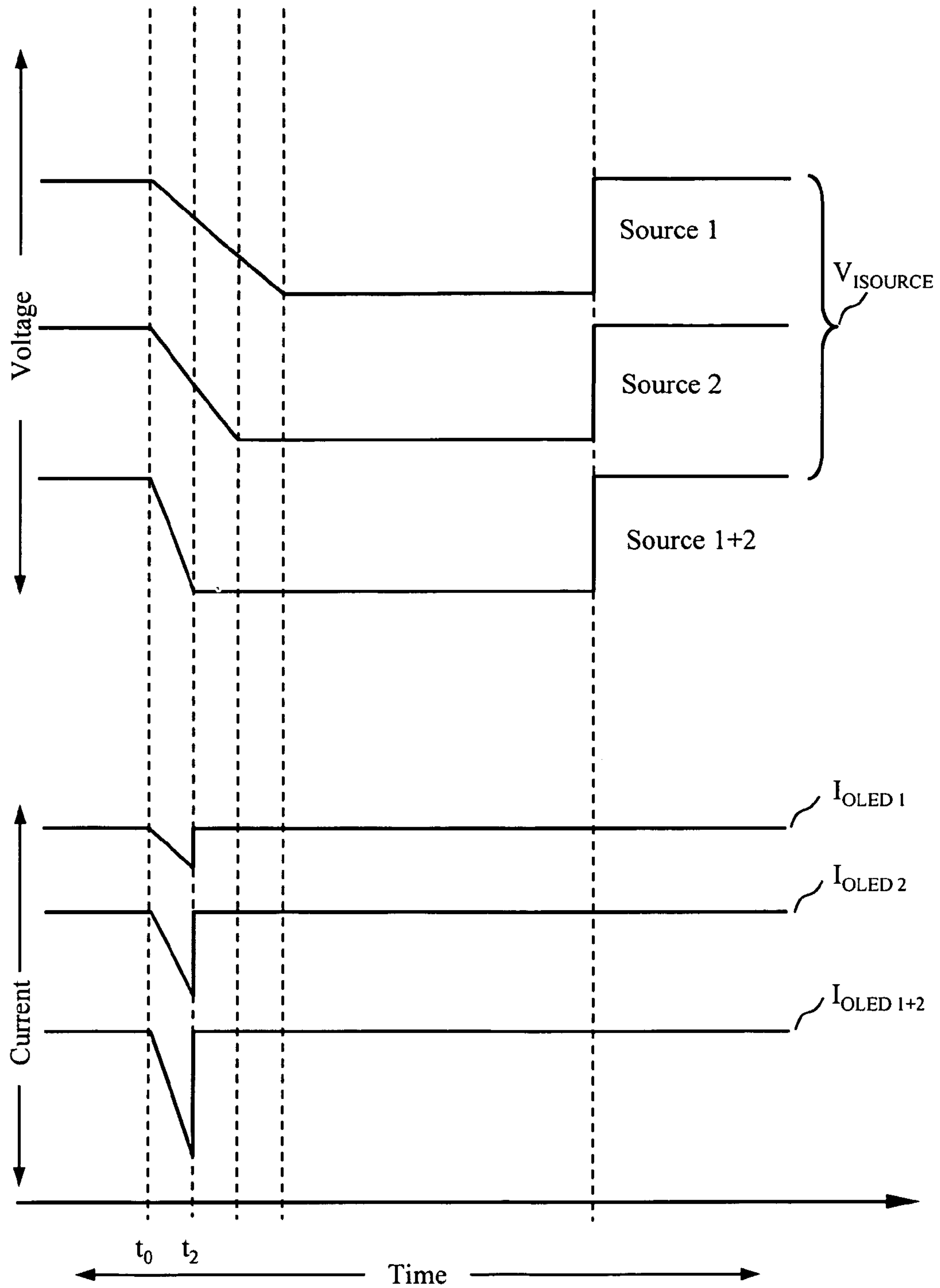

500
+V_LED
114
112
210
V_OLED
I_SOURCE
510
I_SOURCE
116
V_ISOURCE
512
118

Fig. 5



Voltage
Source 1
Source 2
Source 1+2
$V_{ISOURCE}$
Current
$I_{OLED\ 1}$
$I_{OLED\ 2}$
$I_{OLED\ 1+2}$
t_0
t_2
Time

Fig. 5A

ORGANIC LIGHT-EMITTING DIODE (OLED) PRE-CHARGE CIRCUIT FOR USE IN A COMMON ANODE LARGE-SCREEN DISPLAY

TECHNICAL FIELD OF THE INVENTION

The present invention relates to the drive circuitry of a common anode, passive matrix large-screen organic light-emitting diode (OLED) display. More particularly, this invention relates to a pre-charge circuit for optimizing performance.

BACKGROUND OF THE INVENTION

Organic light-emitting diode (OLED) technology incorporates organic luminescent materials that, when sandwiched between electrodes and subjected to a DC electric current, produce intense light of a variety of colors. These OLED structures can be combined into the picture elements or pixels that comprise a display. OLEDs are also useful in a variety of applications as discrete light-emitting devices or as the active element of light-emitting arrays or displays, such as flat-panel displays in watches, telephones, laptop computers, pagers, cellular phones, calculators, and the like. To date, the use of light-emitting arrays or displays has been largely limited to small-screen applications such as those mentioned above.

Demands for large-screen display applications possessing higher quality and higher resolution has led the industry to turn to alternative display technologies that replace older LED and liquid crystal displays (LCDs). For example, LCDs fail to provide the bright, high light output, larger viewing angles, and high resolution and speed requirements that the large-screen display market demands. By contrast, OLED technology promises bright, vivid colors in high resolution and at wider viewing angles. However, the use of OLED technology in large-screen display applications, such as outdoor or indoor stadium displays, large marketing advertisement displays, and mass-public informational displays, is still in the development stage.

Several technical challenges exist relating to the use of OLED technology in a large-screen application. One such challenge is that OLED displays are expected to offer a wide dynamic range of colors, contrast, and light intensity depending on various external environmental factors including ambient light, humidity, and temperature. For example, outdoor displays are required to produce more white color contrast during the day and more black color contrast at night. Additionally, light output must be greater in bright sunlight and lower during darker, inclement weather conditions. The intensity of the light emission produced by an OLED device is directly proportional to the amount of current driving the device. Therefore, the more light output needed, the more current is fed to the pixel. Accordingly, less light emission is achieved by limiting the current to the OLED device.

A pixel, by definition, is a single point or unit of programmable color in a graphic image. However, a pixel may include an arrangement of sub-pixels, for example, red, green, and blue sub-pixels. There are two basic circuit configurations for driving these sub-pixels, namely, a common cathode configuration and a common anode configuration. These configurations differ as to whether the three sub-pixels are addressed via a common cathode line or addressed via a common anode line, respectively. Accordingly, in the common cathode configuration, the cathodes of the three sub-pixels are electrically connected and addressed in common; in the common anode configuration, the anodes of the three sub-pixels are electrically connected and addressed in common.

Conventional OLED displays typically use the common cathode configuration. In a typical common cathode drive circuit, a current source is arranged between each individual anode and a positive power supply, while the cathodes are electrically connected in common to ground. Consequently, the current and voltage are not independent of one another, and small voltage variations result in fairly large current variations, having the further consequence of light output variations. Furthermore, in the common cathode configuration, the constant current source is referenced to the positive power supply, so again any small voltage variation will result in a current variation. For these reasons, the common cathode configuration makes precise control of light emission, which is dependent upon precise current control, more difficult.

By contrast, in a typical common anode drive circuit, a current source is arranged between each individual cathode and ground, while the anodes are electrically connected in common to the positive power supply. As a result, the current and voltage are completely independent of one another, and small voltage variations do not result in current variations, thereby eliminating the further consequence of light output variations. Furthermore, in the common anode configuration, the constant current source is referenced to ground, which does not vary, thereby eliminating any current variations due to its reference. For these reasons, the common anode configuration lends itself to the precise control of light emission needed in a large-screen display application.

Another consideration in a large-screen display application using OLED technology is the physical size of the pixel. A larger emission area is more visible and lends itself to achieving the required wide dynamic range of colors, contrast, and light intensity. Consequently, an OLED device structure having a larger area than OLED structures of conventional small-screen displays is desirable. In a small-screen application, the pixel pitch is typically 0.3 mm or less and the pixel area is, for example, only 0.1 mm^2. By contrast, in a large-screen application, the pixel pitch may be 1.0 mm or greater, thereby allowing the pixel area to be as large as 0.3 to 50 mm^2 (pitch varies up to 10 mm or more with fill factors of 50%). However, a consequence of the larger device area is the relatively high inherent capacitance (C_{OLED}) of the larger OLED device as compared with small OLED structures. Due to this high inherent capacitance, in operation, an additional amount of charge time is required to reach the OLED device working voltage. This charge time limits the on/off rate of the device and thus adversely affects the overall display brightness and performance.

OLED pre-charge circuits have been developed and integrated into the existing drive circuitry to help overcome the capacitance characteristic of OLEDs within a graphics display device. For example, U.S. Pat. No. 6,323,631, entitled, "Constant current driver with auto-clamped pre-charge function," describes a constant current driver with auto-clamped pre-charge function that includes a reference bias generator and a plurality of constant current driver cells, each being connected to the reference bias generator to form a respective current mirror. Each constant current driver cell has a switch transistor, a current output transistor, and a pre-charge transistor. When a constant current is output from the current output transistor for driving an OLED, the pre-charge transistor is turned on to provide a drain to source current as an additional large current for rapidly pre-charging the OLED until the gate to source voltage of the pre-charge transistor is smaller than the threshold voltage. While the pre-charge function of the '631 patent suitably serves to rapidly pre-charge the OLED devices and thereby optimize performance, the pre-charge function of the '631 patent is designed for use in a common cathode drive circuit and is therefore not suitable for use in the common anode drive circuit of a large-screen OLED display device. A further drawback of the pre-charge function of the '631 patent is that it is designed to handle the C_{OLED} value associated with a small pixel area, such as 0.1 mm^2, and is therefore not able to overcome the larger C_{OLED} value associated with a large pixel area.

It is therefore an object of the invention to provide a pre-charge circuit suitable for use in a large-screen OLED display arranged in a common anode configuration.

It is another object of this invention to provide a pre-charge circuit suitable to overcome the large C_{OLED} value associated with the large-area OLED device of a large-screen OLED display arranged in a common anode configuration, thereby optimizing performance.

It is yet another object of this invention to provide a pre-charge circuit that eliminates the effects of varying OLED device characteristics, such as capacitance, due to manufacturing process variations.

SUMMARY OF THE INVENTION

The present invention provides a drive circuitry for a common anode, passive matrix, organic light-emitting diode (OLED) display comprising at least one OLED having an anode and a cathode, the cathode of the OLED being coupled in series to a first current source and a first switching means. The drive circuitry comprises means for pre-charging the at least one OLED before closing the switching means.

The means for pre-charging the at least one OLED may comprise a second switching means. The second switching means may comprise an active switch device, which may comprise a MOSFET. The MOSFET may be an NMOS transistor device having suitable voltage and current ratings for pre-charging the at least one OLED.

The second switching means may be coupled in a branch in parallel over the first current source. If the second switching means comprises a MOSFET, the MOSFET having a gate, the source may be electrically connected to a pre-charge voltage. The MOSFET may also have a drain which is electrically connected to the cathode of the OLED.

The second switching means may comprise a first switch device suitable for coupling the cathode of the OLED to the ground, and a second switch device suitable for coupling; the anode of the OLED to a voltage supply substantially corresponding to the normal operating voltage of the OLED. The first switch device and the second switch device may be active switch devices. The active switch devices may be MOSFET transistors having suitable voltage and current ratings for pre-charging the at least one OLED.

The means for pre-charging the at least one OLED may furthermore comprise a second current source coupled in parallel over the first current source. The second current source may be suitable for supplying a current between 50 and 800 mA, preferably between 100 and 600 mA. The second current source may be substantially identical to the first current source, or it may be different, for example the second current source may be suitable for supplying a current between 2 and 4 times the current supplied by the first current source.

The first current source may be a current source device capable of modifying its output current by selecting either one of a first or a second current reference.

The present invention also provides an arrangement comprising an array of OLEDs, each OLED having an anode common with other OLED's of the array and a cathode, and drive circuitry according to the present invention.

The present invention furthermore provides a common anode, passive matrix, organic light-emitting diode (OLED) display comprising an array of OLEDs, each OLED having an anode and a cathode, the display comprising drive circuitry according to the present invention.

The present invention also provides a method for pre-charging an organic light-emitting diode (OLED) of a common anode, passive matrix OLED display prior to a desired ON-time of the OLED, the method comprising charging the OLED immediately prior to the desired ON-time. The charging may be done by applying a pre-charge voltage to the cathode of the OLED prior to the desired ON-time. Alternatively, it may be done by applying a first voltage level to the anode of the OLED while pulling the cathode of the OLED to a second voltage level, the difference between the first and the second voltage being equal to a desired pre-charge voltage. In this latter case, the first voltage level may be equal to the desired pre-charge voltage, and the second voltage level may be the ground level. According to still another alternative embodiment, the charging may be done by supplying additional current to the OLED prior to the desired ON-time.

The pre-charge voltage may be substantially equal to a normal operating voltage of the OLED during ON-time. At low light output extra gray scales may be obtained by selectively switching two current sources.

These and other characteristics, features and advantages of the present invention will become apparent from the following detailed description, taken in conjunction with the accompanying drawings, which illustrate, by way of example, the principles of the invention. This description is given for the sake of example only, without limiting the scope of the invention. The reference figures quoted below refer to the attached drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1** illustrates a schematic diagram of an OLED array circuit that is representative of a portion of a common anode, passive matrix, large-screen OLED array and associated drive circuit.

FIG. **2**A illustrates a schematic diagram of an OLED drive circuit that is representative of a drive circuit of a single OLED within the OLED array circuit of

FIG. **1**.

FIG. **2**B shows a plot of $V_{ISOURCE}$, thereby illustrating the operation of the OLED drive circuit of FIG. **2**A.

FIG. **3**A illustrates a schematic diagram of an OLED pre-charge circuit in accordance with a first and preferred embodiment of the present invention.

FIG. **3**B shows a plot of $V_{ISOURCE}$ VS. $+V_{PRE\text{-}CHARGE}$, thereby illustrating the operation of OLED the pre-charge circuits of FIGS. **3**A, **4**, **5**, and **6**.

FIG. **4** illustrates a schematic diagram of an OLED pre-charge circuit in accordance with a second embodiment of the present invention.

FIG. **5** illustrates a schematic diagram of an OLED pre-charge circuit in accordance with a third embodiment of the present invention.

FIG. **5**A illustrates the result on voltage and current in function or time, of using two current sources as in FIG. **5**

FIG. **6** illustrates a schematic diagram of an OLED pre-charge circuit in accordance with a fourth embodiment of the present invention.

In the different figures, the same reference figures refer to the same or analogous elements.

DESCRIPTION OF ILLUSTRATIVE EMBODIMENTS

The present invention will be described with respect to particular embodiments and with reference to certain drawings but the invention is not limited thereto but only by the claims. The drawings described are only schematic and are non-limiting. In the drawings, the size of some of the elements may be exaggerated and not drawn on scale for illustrative purposes.

Furthermore, the terms first, second, third and the like in the description and in the claims, are used for distinguishing between similar elements and not necessarily for describing a sequential or chronological order. It is to be understood that the terms so used are interchangeable under appropriate circumstances and that the embodiments of the invention described herein are capable of operation in other sequences than described or illustrated herein.

It is to be noticed that the term "comprising", used in the claims, should not be interpreted as being restricted to the means listed thereafter; it does not exclude other elements or steps. Thus, the scope of the expression "a device comprising means A and B" should not be limited to devices consisting only of components A and B. It means that with respect to the present invention, the only relevant components of the device are A and B.

The present invention will mainly be described with reference to a single display but the present invention is not limited thereto. For instance, the display may be extendable, e.g. via tiling, to form larger arrays. Hence, the present invention may also include assemblies of pixel arrays, e.g. they may be tiled displays and may comprise modules made up of tiled arrays which are themselves tiled into supermodules. Thus, the word display relates to a set of addressable pixels in an array or in groups of arrays. Several display units or "tiles" may be located adjacent to each other to form a larger display, i.e. multiple display element arrays are physically arranged side-by-side so that they can be viewed as a single image.

In one aspect of the present invention a pre-charge circuit is provided which may be integrated within the drive circuitry of a common anode, passive matrix, OLED display device in order to overcome the inherent capacitance characteristic, C_{OLED}, of the OLED devices therein. The display may be a large-screen display. More specifically, in an aspect of the present invention a first pre-charge circuit of the present invention applies a pre-charge voltage to the cathode of a given OLED device just prior to the desired "on" time, thereby charging the OLED device rapidly. A second pre-charge circuit of the present invention applies a pre-charge voltage to the anode of a given OLED device while concurrently pulling the cathode to ground just prior to the desired on time, thereby charging the OLED device rapidly. A third pre-charge circuit of the present invention simply supplies additional current to the OLED device just prior to the desired on time, thereby charging the OLED device rapidly. Finally, a fourth pre-charge circuit of the present invention comprises a single current source device that is capable of modifying its output current rapidly by selecting either a low or high current reference, thus being able to rapidly charge the OLED device.

FIG. **1** illustrates a schematic diagram of an OLED array circuit **100**, which is representative of a portion of a typical common anode, passive matrix, large-screen OLED array and associated drive circuit. OLED array circuit **100** includes an OLED array **110** formed of a plurality of OLEDs **112** (each having an anode and cathode, as is well known) arranged in a matrix of rows and columns. For example, OLED array **110** is formed of OLEDs **112***a*, **112***b*, **112***e*, **112***d*, **112***e*, **112***f*, **112***g*, **112***h*, and **112***j* arranged in a 3×3 array, where the anodes of OLEDs **112***a*, **112***b*, and **112***c* are electrically connected to a ROW LINE 1, the anodes of OLEDs **112***d*, **112***e*, and **112***f* are electrically connected to a ROW LINE 2, and the anodes of OLEDs **112***g*, **112***h*, and **112***j* are electrically connected to a ROW LINE **3**. Furthermore, the cathodes of OLEDs **112***a*, **112***d*, and **112***g* are electrically connected to a COLUMN LINE A, the cathodes of OLEDs **112***b*, **112***e*, and **112***h* are electrically connected to a COLUMN LINE B, and the cathodes of OLEDs **112***c*, **112***f*, and **112***j* are electrically connected to a COLUMN LINE C. Each OLED **112** represents a pixel in monochrome displays or a sub-pixel in a color display (typically red, green, or blue, however, any color variants are acceptable. Sub-pixels are geometrically grouped together to form single addressable full color pixels, for instance **112***a*–*c* may be respectively red, green and blue). An OLED emits light when forward biased in conjunction with an adequate current supply, as is well known.

A positive voltage ($+V_{LED}$), typically ranging between 5 volts (i.e., normal working voltage across the OLED+voltage over current source, usually 0.7 V) and 15–20 volts, is electrically connected to each respective row line ROW LINE 1, ROW LINE 2, ROW LINE 3 via a plurality of switches **114***a*, **114***b*, **114***e*. Switches **114***a*, **114***b*, **114***c* are conventional active switch devices, such as MOSFET switches or transistors having suitable voltage and current ratings. More specifically, a positive voltage $+V_{LED}$ is electrically connected to ROW LINE 1 via switch **114***a*, to ROW LINE 2 via switch **114***b*, and to ROW LINE 3 via switch **114***e*. Column lines COLUMN LINE A, COLUMN LINE B, and COLUMN LINE C are driven by separate constant current sources, i.e., a plurality of current sources (I_{SOURCE}) **116***a*, **116***b*, **116***c*. More specifically, current source I_{SOURCE} **116***a* drives COLUMN LINE A, current source I_{SOURCE} **116***b* drives COLUMN LINE B, and current source I_{SOURCE} **116***c* drives COLUMN LINE C. Connected in series between current source I_{SOURCE} **116***a* and ground is a switch **118***a*. Connected in series between current source I_{SOURCE} **116***b* and ground is a switch **118***b*. Connected in series between current source I_{SOURCE} **116***c* and ground is a switch **118***c*. Current sources I_{SOURCE} **116***a*, **116***b*, **116***c* are conventional current sources capable of supplying a constant current typically in the range of 5 to 50 mA. Examples of constant current devices include a Toshiba TB62705 (8-bit constant current LED driver with shift register and latch functions) and a Silicon Touch ST2226A (PWM-controlled constant current driver for LED displays). Switches **118***a*, **118***b*, **118***c* are normally included in the current source integrated circuit and consist of a conventional active switch device, such as MOSFET switches or transistors having suitable voltage and current ratings.

The matrix of OLEDs **112***a*–**112***j* within OLED array circuit **100** are arranged in the common anode configuration.

For each colour pixel for instance on ROW LINE **2**, the anodes of each sub-pixel **112***d*–**112***f* are all connected to the same row line. In this way the current source is referenced to the ground and the current and voltage are independent of one another providing better control of the light emission.

In operation, to activate (light up) any given OLED **112***a*–**112***j*, its associated row line ROW LINE 1, ROW LINE 2, ROW LINE 3 and column line COLUMN LINE A, COLUMN LINE B, COLUMN LINE C are activated by simultaneously closing their associated switches **114***a*, **114***b*, **114***c* and **118***a*, **118***b*, **118***c*. In a first example, to light up OLED **112***b*, a positive voltage $+V_{LED}$ is applied to ROW LINE 1 by closing switch **114***a* and, simultaneously, a constant current is supplied to COLUMN LINE B via current source I_{SOURCE} **116***b* by closing switch **118***b*. In this way, OLED **112***b* is forward biased and current flows through OLED **112***b*. Once a device threshold voltage (of typically 1.5–2 volts) across the OLED **112***b* is reached, the OLED **112***b* starts emitting light. OLED **112***b* remains lit up as long as switch **114***a* and switch **118***b* retrain closed. To deactivate OLED **112***b*, switch **118***b* is opened. In a second example, to light up OLED **112***g*, a positive voltage $+V_{LED}$ is applied to ROW LINE 3 by closing switch **114***c* and, simultaneously, a constant current is supplied to COLUMN LINE A via current source I_{SOURCE} **116***a* by closing switch **118***a*. In this way, OLED **112***g* is forward biased and current flows through OLED **112***g*. Once the device threshold voltage (of typically 1.5–2 volts) across the OLED **112***g* is reached, OLED **112***g* starts emitting light. OLED **112***g* remains lit up as long as switch **114***c* and switch **118***a* remain closed. To deactivate OLED **112***g*, switch **118***a* is opened.

Along a given row line ROW LINE 1, ROW LINE 2, ROW LINE 3, any one or more OLEDs **112***a*–**112***j* may be activated at any given time. By contrast, along a given column line COLUMN LINE A, COLUMN LINE B, COLUMN LINE C, only one OLED **112** may be activated at any given time. Thus, a complete image is built from sequentially or randomly selecting each row of OLED array **110**, by closing its corresponding switch **114***a*–**114***c*. In each row a current with a certain intensity and a certain duration is sent through the diodes **112***a*–**112***c*, **112***d*–**112***f*, **112***g*–**112***j* on that row by current sources **116***a*, **116***b*, **116***e* by closing and opening switches **118***a*, **118***b*, **118***c*, such as to display the correct intensity in each pixel or sub-pixel. A switch **114***a*, **114***b*, **114***c* remains closed as long as its row is selected and opens when the next row is selected. All switches **118***a*, **118***b*, **118***c* open before the next row is selected. Further details of the operation of any given OLED **112***a*–**112***j* is found in reference to FIGS. **2**A and **2**B below.

FIG. **2**A illustrates a schematic diagram of an OLED drive circuit **200**, which is representative of a typical drive circuit of a single OLED **112** within OLED array circuit **100** of FIG. **1**. OLED drive circuit **200** includes switch **114**, OLED **112**, current source I_{SOURCE} **116**, and switch **118** all arranged in series between positive voltage $+V_{LED}$ and ground as shown in FIG. **2**A. OLED drive circuit **200** further includes a capacitor **210** arranged in parallel with OLED **112**. Capacitor **210** is representative of the device capacitance (C_{OLED}) of OLED **112**. Given the area of the structure of OLED **112**, a typical value of C_{OLED} can be more than 500 pF, which is relatively high compared with a usual C_{OLED} value of 5 pF for a small OLED structure used in a small-screen OLED display application. The value of C_{OLED} along with any additional line capacitance of the physical package, which for the purpose of this description are assumed to be negligible, must be overcome in order to achieve satisfactory display performance. A voltage V_{OLED} represents the voltage potential across OLED **112** and a voltage $V_{ISOURCE}$ represents the voltage potential across the series-connected current source I_{SOURCE} **116** and switch **118**.

FIG. **2**B shows a plot **250** of the voltage potential $V_{ISOURCE}$ across the series-connected current source **116** and switch **118**, from a time t0, when switches **114** and **118** are closed, to a time t2, when switch **118** is opened, thereby illustrating the operation of OLED drive circuit **200**. At time t0, the value of $V_{ISOURCE}$ is equal to positive voltage $+V_{LED}$ and begins to fall slowly towards the working voltage ($V_{WORKING}$) of OLED **112** due to the relatively high capacitance value C_{OLED} of the OLED **112**. The OLED starts lighting up a little bit as soon as the threshold level or threshold voltage is reached (the threshold voltage of an OLED is the voltage across the OLED just enough to let it light up; the normal operating voltage or working voltage across the OLED is higher than this threshold voltage). $V_{ISOURCE}$ reaches the working voltage of OLED **112** at a time t1. The period between t0 and t1 represents the charge time T_{CHARGE} of capacitor **210** of OLED **112**. The voltage transition from t0 to t1 is linear because the current output of current source I_{SOURCE} **116** is constant. At time t1, OLED **112** begins to emit its full light and continues to emit light for a predetermined period of time which is the OLED emission time T_{ON} as long as switches **114** and **118** remain closed. OLED **112** is deactivated by opening switch **118**, and subsequently $V_{ISOURCE}$ returns sharply to the $+V_{LED}$ value. OLED **112** remains off for a period from t2 to the next t0, i.e., OLED off time or period T_{OFF}. Therefore, a cycle time T_{CYCLE} is represented by $T_{CHARGE}+T_{ON}+T_{OFF}$. As shown in plot **250**, T_{CHARGE} represents time wasted when switches **114** and **118** are closed and capacitor **210** is charging but OLED **112** is not yet emitting light at the desired emission level. This results in an extended T_{CYCLE}, thereby decreasing the achievable T_{ON}/T_{OFF} rate and limiting the achievable performance of OLED drive circuit **200**. FIGS. **3**A, **3**B, **4**, **5**, and **6** that follow illustrate ways to minimize or eliminate the T_{CHARGE} time by performing a pre-charge operation on capacitor **210**, thereby minimizing T_{CYCLE}.

FIG. **3**A illustrates a schematic diagram of an OLED pre-charge circuit **300** in accordance with a first and preferred embodiment of the invention. OLED pre-charge circuit **300** is identical to OLED drive circuit **200** of FIG. **2**A except for the addition of a MOSFET **310** arranged in parallel with current source I_{source} **116**. More specifically, the drain of MOSFET **310** is electrically connected directly to the cathode of OLED **112**, the source of MOSFET **310** is connected to a pre-charge voltage$+V_{PRE\text{-}CHARGE}$, and the gate of MOSFET **310** is electrically connected to a pre-charge control voltage $V_{PRECHARGE\text{-}CONTROL}$. MOSFET **310** may be any conventional NMOS transistor device having suitable voltage and current ratings for this application. However, MOSFET **310** is representative of any suitable active switch device.

FIG. **3**B shows a plot **350** of $V_{ISOURCE}$ vs. $+V_{PRE\text{-}CHARGE}$ from a time t0, when the pre-charge operation begins, to a time t2, when switch **118** is opened, thereby illustrating the operation of OLED pre-charge circuit **300**. (It is to be noted that the plot of $V_{ISOURCE}$ vs. $+V_{PRE\text{-}CHARGE}$ is not drawn to scale in relation to one another along the voltage axis. Plot **350** is intended to illustrate only general voltage transitions and timing.) At tune t0, MOSFET **310** is switched on by applying a voltage $V_{PRECHARGE\text{-}CONTROL}$ its gate, which voltage $V_{PRECHARGE\text{-}CONTROL}$ is positive enough referred to the source of MOSFET **310** (voltage$=+V_{PRECHARGE}$) to saturate MOSFET **310**. MOSFET **310** connects a source that is able to sink typically 100 to 600 ma of current. In addition, at time t0 switch **114** is closed, while switch **118** remains open. As a result, current begins to flow through OLED **112** for a short period of time via the electrical path created by MOSFET **310**. This time period must be long enough to build up a voltage across capacitor **210** of OLED **112** that approaches the working voltage of OLED **112**. Once this voltage has built up across capacitor **210** of OLED **112**, MOSFET **310** is switched off, i.e., the $+V_{PRE\text{-}CHARGE}$ voltage at the cathode of the OLED is removed, and switch **118** is simultaneously closed, thereby allowing the normal operating current from current source (SOURCE **116** to flow through OLED **112**, causing light to be emitted.

Plot **350** of FIG. **3**B shows that the value of $V_{ISOURCE}$ is equal to $+V_{LED}$ at t0 when $V_{PRECHARGE\text{-}CONTROL}$ is applied (MOSFET **310** on), switch **114** is closed, and switch **118** is open. Subsequently, $V_{ISOURCE}$ falls sharply toward the working voltage of OLED **112** due to $+V_{PRE\text{-}CHARGE}$ rapidly charging capacitor **210**. At t1, $V_{PRECHARGE\text{-}CONTROL}$ is removed and switch **118** is closed. The period between t0 and t1 represents the charge time T_{CHARGE} of capacitor **210** of OLED **112**. At time t1, OLED **112** begins normal light emission and continues to emit light for a predetermined period of time T_{ON} as long as switches **114** and **118** remain closed. Thus, switch **114** is closed for a period of time equal to at least charge time T_{CHARGE}+OLED emission time T_{ON}, while switch **118** is closed for a period of time equal to the OLED emission time T_{ON}. OLED **112** is deactivated by opening switch **118**, and subsequently $V_{ISOURCE}$ returns sharply to the $+V_{LED}$ value. OLED **112** remains off for a period from t2 to the next t0, i.e., OLED off tune T_{OFF}. Therefore, a cycle time T_{CYCLE} is represented by $T_{CHARGE}+T_{ON}+T_{OFF}$.

With reference to plot **250** of FIG. **2**A and plot **350** of FIG. **3**A, it is illustrated that charge time T_{CHARGE} of OLED pre-charge circuit **300**, which is typically in the range of 12 ns to 50 ns, is significantly minimized compared with the charge time T_{CHARGE} of OLED drive circuit **200**, which is typically in the range of 25 ns to 65 μs. As a result, T_{CYCLE} of OLED pre-charge circuit **300** is allowed to be significantly shorter than T_{CYCLE} of OLED drive circuit **200** while achieving equivalent T_{ON} time. Consequently, the achievable T_{ON}/T_{OFF} rate of OLED **112** within OLED pre-charge circuit **300** is increased compared with the achievable on/off rate of OLED **112** within OLED drive circuit **200**, thereby enhancing overall performance.

Is it important to balance the operation of OLED pre-charge circuit **300** such that charge time T_{CHARGE} is minimized while also ensuring that pre-charging stops when the working voltage of OLED **112** has been reached. Consequently, if the timing of the pre-charging is too long, it will result in an excessive current through OLED **112**, which results in excessive light emission. As a precaution, it may be desirable to end the pre-charge operation just short of $V_{ISOURCE}$ reaching the normal operating voltage of 0.7 volts. For example, $V_{PRECHARGE\ CONTROL}$ Can be removed when $V_{ISOURCE}$ reaches 1.5 volts. This would result in a slightly longer charge time T_{CHARGE}, as the voltage transition from 1.5 to 0.7 volts is due to the current supplied by current source I_{SOURCE} **116** only, without the help of $+V_{PRE\text{-}CHARGE}$.

Furthermore, when the OLED emission time T_{ON}=0, the pre-charge operation must not occur, so that OLED **112** is not lighted up when it is unwanted. In this case, both switch **118** and MOSFET **310** remain open. If the pre-charge operation was allowed when OLED emission time T_{ON}=0, OLED **112** could possibly begin lighting up because $+V_{PRE\text{-}CHARGE}$ reaches a level just high enough to slightly light up OLED **112**.

Thus, unwanted lighting of OLED **112** should be avoided by eliminating the pre-charge operation if OLED emission time T_{ON}=0.

In summary, and in reference to FIGS. **3**A and **3**B, just prior to the desired T_{ON} time, a pre-charge voltage ($V_{PRE\text{-}CHARGE}$) from a source that is able to sink a suitable amount of current is applied to the OLED cathode via MOSFET **310**. Thus, capacitor **210** is charged rapidly, not via the normal current source (I_{SOURCE} **116**), but instead via a high current through MOSFET **310**.

FIG. **4** illustrates a schematic diagram of an OLED pre-charge circuit **400** in accordance with a second embodiment of the invention. OLED pre-charge circuit **400** is identical to OLED drive circuit **200** of FIG. **2** except that a voltage V_{OLED} may be electrically connected to the anode of OLED **112** via a switch **410**, and the cathode of OLED **112** may be electrically connected to ground via a switch **412**. Switches **410** and **412** are conventional active switch devices, such as MOSFET switches or transistors having suitable voltage and current ratings.

In operation, just prior to the desired OLED emission time T_{ON} (see FIG. **3**B) the anode of OLED **112** is forced to the normal operating voltage across the OLED **112** (V_{OLED}) for a short time by closing switch **410**, while concurrently shorting the cathode of OLED **112** to ground by closing switch **412**. In this way, a charge is built up across capacitor **210** rapidly. After a predetermined amount of time (i.e., charge time T_{CHARGE} of FIG. **3**B), switches **114** and **118** are closed and switch **412** is opened, thereby applying $+V_{LED}$ to the anode of OLED **112** and supplying the normal operating current via current source I_{SOURCE} **116**. As a result, OLED **112** begins its normal operation (i.e., T_{ON} of FIG. **3**B).

Similar to OLED pre-charge circuit **300** of FIG. **3**A, T_{CHARGE} of OLED pre-charge circuit **400**, which is typically in the range of 12 ns to 50 ns, is significantly minimized compared with charge time T_{CHARGE} of OLED drive circuit **200**, which is typically in the range of 25 ns to **65** μ*s*. A*s* a *result*, T_{CYCLE} of OLED pre-charge circuit **400** is allowed to be significantly shorter than T_{CYCLE} of OLED drive circuit **200** while achieving equivalent OLED emission time T_{ON}. Consequently, the achievable T_{ON}/T_{OFF} rate of OLED **112** within OLED pre-charge circuit **400** is increased compared with the achievable on/off rate of OLED **112** within OLED drive circuit **200**, thereby enhancing overall performance.

In summary, and in reference to FIG. **4**, just prior to the desired OLED emission time T_{ON}, a pre-charge voltage ($+V_{OLED}$) is applied to the anode of OLED **112** while, concurrently, the cathode of OLED **112** is pulled to ground; thus, capacitor **210** is charged rapidly, not via the normal current source (I_{SOURCE} **116**), but instead via $+V_{OLED}$ and the straight connection of the cathode to the ground.

FIG. **5** illustrates a schematic diagram of an OLED pre-charge circuit **500** in accordance with a third embodiment of the invention. OLED pre-charge circuit **500** is identical to OLED drive circuit **200** of FIG. **2**, except that an additional current source (i.e., a current source I_{SOURCE} **510** with an associated series-connected switch **512**) is connected in parallel with current source I_{SOURCE} **116**, as shown in FIG. **5**. Current source I_{SOURCE} **510** is a conventional current source capable of supplying a constant current typically in the range of 100 to 600 mA. Switch **512** is a conventional active switch device, such as a MOSFET switch or transistor having suitable voltage and current ratings.

In operation, just prior to the desired T_{ON} time (see FIG. **3**B) switches **114**, **118** and **512** are all closed, thus additional current is available via current source I_{SOURCE} **510** along with the normal current supplied via current source I_{SOURCE} **116**. As a result of the additional current availability, the charge time (i.e., T_{CHARGE} of FIG. **3**B) of capacitor **210** is reduced. In this way, a charge is built up across capacitor **210** rapidly. After a predetermined amount of time (i.e., T_{CHARGE} of FIG. **3**B), switch **512** is opened, thereby allowing only the normal operating current via current source I_{SOURCE} **116**. As a result, OLED **112** begins its normal operation (i.e., T_{ON} of FIG. **3**B).

Similar to OLED pre-charge circuit **300** of FIG. **3**A and OLED pre-charge circuit **400** of FIG. **4**, charge time T_{CHARGE} of OLED pre-charge circuit **500**, which is typically in the range of 12 ns to 50 ns, is significantly minimized compared with charge time T_{CHARGE} of OLED drive circuit **200**, which is typically in the range of 25 ns to 65 µs. As a result, T_{CYCLE} of OLED pre-charge circuit **400** is allowed to be significantly shorter than T_{CYCLE} of OLED drive circuit **200** while achieving equivalent OLED emission time T_{ON}. Consequently, the achievable T_{ON}/T_{OFF} rate of OLED **112** within OLED pre-charge circuit **500** is increased compared with the achievable on/off rate of OLED **112** within OLED drive circuit **200**, thereby enhancing overall performance.

In summary, and in reference to FIG. **5**, just prior to the desired T_{ON} time, capacitor **210** is charged rapidly, not via the normal current source (I_{SOURCE} **116**) only, but with the additional current available to OLED **112** via current source I_{SOURCE} **510**.

The charge time T_{CHARGE} used for pre-charge, greatly influences the performance of a display. Longer pre-charge times T_{CHARGE}, limit the maximum light output while compensating by increasing the current level increases the lowest light output and thus eliminates gray scales. High quality displays need a large number of gray scales, thus requiring a high digital resolution or number of possible output values or current sources operating at high clock speeds. A single current pulse (one clock cycle) will only generate light if the threshold is reached within that pulse, for instance in half the time of a clock cycle. If f_c is the clock frequency, then the shortest t2–t0 is $1f_c$. For example a 40 MHz clock, the pre-charge time T_{CHARGE} would then have to be as short as 12 ns. For OLED diodes typically operating in the range of 9–15 V and a large C_{OLED} of 500 pF, a pre-charge current of at least 375 mA (C_{OLED}*dV/dt) is required, which is quite high. However, the requirement of reaching the pre-charge state within a clock pulse period maybe overcome by using two current sources **116**, **510** as in FIG. **5**.

FIG. **5**A, demonstrates the possible result of using two current sources **116** and **510** as in FIG. **5**. Current source **510** is for instance capable of delivering twice the current of current source **116**. That means that $V_{ISOURCE}$ of current source **510** reaches the threshold voltage in half the time of $V_{ISOURCE}$ of current source **116**. Consequently, when both current sources **510**, **116** operate simultaneously, $V_{ISOURCE}$ will reach the threshold in a third of the time. In the lower part of FIG. **5**A, corresponding currents I_{OLED} through the OLED **112** are shown for a t1–t0 equal to the time required for the two current sources **510**, **116** to together reach the threshold. The surface under the current curve is a measure for the emitted light. As can be seen, even though $V_{ISOURCE}$ for each current source **510**, **116** separately does not necessarily reach the threshold within the on time, three possible light output values are generated as long as the reached V_{OLED} (not drawn in FIG. **5**A) is high enough for the diode **112** to start emitting light. Expanding on this principle, at low light output values highly precise gray scales can be obtained by varying the on time of one or two current sources **510**, **116**. Additionally, high current can be obtained at high light output by switching on both current sources **510**, **116**.

FIG. **6** illustrates a schematic diagram of an OLED pre-charge circuit **600** in accordance with a fourth embodiment of the invention. OLED pre-charge circuit **600** is identical to OLED drive circuit **200** of FIG. **2**, except that current source I_{SOURCE} **116** is replaced with a current source I_{SOURCE} **610**, which is a single current source device that is capable of modifying its output current rapidly by selecting either a low or high current reference via a switch **612** and a switch **614**, respectively. Switches **612** and **614** are conventional active switch devices, such as MOSFET switches or transistors having suitable voltage and current ratings.

In operation and with reference to FIGS. **3**B and **6**, during charge time T_{CHARGE} switches **114**, **118** and **612** are closed and switch **614** is open, thereby supplying the high current reference to current source I_{SOURCE} **610** and thus charging capacitor **210** rapidly. Once the pre-charge operation is complete, switch **612** is opened and switch **614** is closed, thereby supplying the low current reference to current source I_{SOURCE} **610**. As a result, current source I_{SOURCE} **610** rapidly drops to the normal constant operating current. Switches **114**, **118**, and **614** remain closed for the duration of OLED emission time T_{ON} and normal operation occurs. At time t2 switch **118** is opened, thus ending OLED emission time T_{ON}.

Lastly, because the pre-charge circuits of the present invention overcome the adverse performance effects due to C_{OLED}, any process variations affecting C_{OLED} do not factor into the OLED overall display performance. Thus, the pre-charge circuits of the present invention eliminate the effects of varying OLED device characteristics, such as capacitance, due to manufacturing process variations.

The invention claimed is:

1. Drive circuitry for a common anode, passive matrix, organic light-emitting diode (OLED) display comprising at least one OLED having an anode and a cathode, the cathode of the OLED being coupled in series to a first current source and a first switching means, and the anode of the OLED being coupled in series to a second switching means, wherein the drive circuitry is adapted so that one cycle for the at least one OLED consists of a charge time of the OLED which starts with the voltage between the cathode and anode of the OLED being zero, followed by pre-charging the at least one OLEO to a strictly positive voltage level before closing the first switching means, followed by maintaining a working voltage for the ON-time, followed by an OFF-time in which the cathode voltage returns to the voltage at the anode after which the cycle is repeated.

2. Drive circuitry according to claim **1**, wherein the means for pre-charging the at least one OLED comprises a third switching means.

3. Drive circuitry according to claim **2**, wherein the third switching means comprises an active switch device.

4. Drive circuitry according to claim **3**, wherein the active switch device comprises a MOSFET.

5. Drive circuitry according to claim **4**, wherein the MOSFET is an NMOS transistor device having suitable voltage and current ratings for pre-charging the at least one OLED.

6. Drive circuitry according to claim **2**, wherein the third switching means is coupled in a branch in parallel over the first current source.

7. Drive circuitry according to claim **4**, the MOSFET having a source, wherein the source is electrically connected to a pre-charge voltage.

8. Drive circuitry according to claim **7**, the MOSFET having a drain, wherein the drain of the MOSFET is electrically connected to the cathode of the OLED.

9. Drive circuitry according to claim **2**, wherein the third switching means comprises a first switch device suitable for coupling the cathode of the OLED to the ground, and a second switch device suitable for coupling the anode of the OLED to a voltage supply substantially corresponding to the normal operating voltage of the OLEO.

10. Drive circuitry according to claim **9**, wherein the first switch device and the second switch device are active switch devices.

11. Drive circuitry according to claim **10**, wherein the active switch devices are MOSFET transistors having suitable voltage and current ratings for pre-charging the at least one OLED.

12. Drive circuitry according to claim **2**, wherein the means for pre-charging the at least one OLED furthermore comprises a second current source coupled in parallel over the first current source.

13. Drive circuitry according to claim **12**, wherein the second current source is suitable for supplying a current between 50 and 800 mA.

14. Drive circuitry according to claim **12**, wherein the second current source is substantially identical to the first current source.

15. Drive circuitry according to claim **12**, wherein the second current source is suitable for supplying a current between 2 and 4 times the current supplied by the first current source.

16. Drive circuitry according to claim **2**, wherein the first current source is a current source device capable of modifying its output current by selecting either one of a first or a second current reference.

17. An arrangement comprising:

an array of OLEDs, each OLED having an anode common with other OLED's of the array and a cathode, and

drive circuitry according to claim **1**.

18. A common anode, passive matrix, organic light-emitting diode (OLED) display comprising an array of OLEDs, each OLED having an anode and a cathode, the display comprising drive circuitry according to claim **1**.

19. A method for pre-charging an organic light emitting diode (OLED) of a common anode, passive matrix OLED display prior to a desired ON-time of the OLED, one cycle for the OLED consisting of a charge time of the OLED which starts with the voltage between the cathode and anode of the OLED being zero, charging the OLED to a strictly positive voltage level immediately prior to the desired ON-time, followed by maintaining the working voltage for the ON-time, followed by an OFF-time in which the cathode voltage returns to the voltage at the anode, after which the cycle is repeated, wherein the charging is done by applying a pre-charge voltage to the cathode of the OLED prior to the desired ON-time.

20. A method according to claim **19**, wherein the pre-charge voltage is substantially equal to a normal operating voltage of the OLED during ON-time.

21. A method for pre-charging according to claim **20** and where at low light output extra gray scales are obtained by selectively switching two current sources.

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