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Multiplexed column drivers for passive-matrix control

Abstract

A passive-matrix controller provides a control signal to each column of multiple columns of components, a driver for each column wire, and a multiplexer. Each column of components is connected to a column wire. The driver provides a drive signal in response to the control signal and the multiplexer comprises an output connected to each column wire and an input connected to each driver and connects the inputs to the outputs in response to a multiplex signal from the passive-matrix controller. The components can be inorganic micro-light-emitting diodes.

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Background/Summary

FIELD OF THE DISCLOSURE

(1) The present disclosure relates to passive-matrix display architectures having row and column control signals.

BACKGROUND OF THE DISCLOSURE

(2) Flat-panel displays are widely used in conjunction with computing devices, in portable

electronic devices, and for entertainment devices such as televisions. Such displays typically employ an array of pixels distributed over a display substrate to display images, graphics, or text. In a color display, each pixel includes light emitters that emit light of different colors, such as red, green, and blue. For example, liquid crystal displays (LCDs) employ liquid crystals to block or transmit light from a backlight behind the liquid crystals and organic light-emitting diode (OLED) displays rely on passing current through a layer of organic material that glows in response to the current. Displays using inorganic light-emitting diodes (LEDs) as pixel elements are also in widespread use for outdoor signage and have been demonstrated in a 55-inch television.

(3) Displays are typically controlled with either a passive-matrix (PM) control scheme employing electronic pixel control circuitry external to the pixel array or an active-matrix (AM) control scheme employing electronic pixel control circuitry in each pixel on the display substrate and associated with each light-emitting element. Both OLED displays and LCDs using passive-matrix control and active-matrix control are available. An example of such an AM OLED display device is disclosed in U.S. Pat. No. 5,550,066. In a PM-controlled display, each pixel in a row is stimulated to emit light at the same time while the other rows do not emit light, and each row is sequentially activated at a high rate to provide the illusion that all of the rows simultaneously emit light. In contrast, in an AM-controlled display, pixel data is concurrently provided to and stored in pixels in a row and the rows are sequentially activated to load the data in the activated row. While data is loaded into one row, the other rows of pixels can emit light corresponding to the pixel data stored in the pixels.

(4) Displays are typically controlled by a display controller that can include or communicate with a column controller for providing column-data signals to columns of pixels and a row controller for providing row-select signal to rows of pixels. The row and column controllers are generally provided in integrated circuits constructed on a semiconductor substrate. Although the construction of semiconductor wafers is carefully controlled, the semiconductor epitaxy, the semiconductor material in which circuits are formed, does vary spatially over the extent of the semiconductor substrate. Moreover, as circuits, components, or devices shrink (become smaller) in size, the variation between the circuits, components, or devices increases, because the area of the circuits, components, or devices decreases so that local changes in epitaxy have a relative larger effect in the smaller circuit, component, or device (e.g., as described with Pelgrom scaling). This variation consequently leads to variable circuit operation. In particular, analog circuits that provide variable voltages and currents can experience considerable performance variation.

SUMMARY

(5) When applied to rows or columns of light emitters, the variation in voltage and current between rows or columns controlled by different circuits can lead to a visible non-uniformity in light output between different rows or columns of light emitters controlled by the circuit with a common control signal. The human visual system is very sensitive to such variation, so there is an on-going need for improvements in light emitter control in passive-matrix systems. The present disclosure addresses this ongoing need by providing embodiments of a controller that includes a multiplexer. The controller can be used in a passive-matrix display design. The multiplexer can act to physically and/or temporally reroute signals so that the observable variation is reduced as compared to a similar design that does not use the multiplexer.

(6) The present disclosure includes, among various embodiments, a passive-matrix controller for providing a control signal to each column of multiple columns of components, each column of components connected to an individual column wire. Each component comprises a column driver for each column wire, the column driver providing a drive signal in response to the control signal, and a multiplexer comprising an output connected to each column wire and an input connected to each column driver. The multiplexer uniquely connects each input to an output in response to a multiplexer control signal provided by the passive-matrix controller that specifies multiplexer connections between the inputs and the outputs to provide each drive signal to an output. The

column drivers can each drive a column of pixels or light emitters in a display, for example a passive-matrix display, or the column drivers can be cluster column drivers that can each drive a column of pixels or light emitters in a cluster of pixels in a display.

(7) In some embodiments, a passive-matrix controller for providing a signal to each column of columns of components, each of the columns of components connected to an individual column wire, the controller comprises column drivers, one for each column wire individually connected to one of the columns of components, each of the column drivers providing a drive signal in response to a control signal; and a multiplexer comprising outputs and inputs, each of the outputs connectable to the column wire individually connected to one of the columns of components and each of the inputs connected to one of the column drivers. The multiplexer can be operable to uniquely connect each of the inputs to one of the outputs in response to a multiplexer control signal provided by the passive-matrix controller to provide the drive signal from one of the column drivers to one of the outputs.

(8) In some embodiments, the control signals are analog signals. The analog control signals can be voltage signals or current signals. In some embodiments, the control signals are digital signals. The digital control signals can be data signals, timing signals, or pulse-width modulation signals.

(9) Embodiments of the passive-matrix controller can comprise a first input, a second input, a first output, and a second output. During a first time period the column multiplexer can connect the first input to the first output and the second input to the second output and during a second time period the column multiplexer can connect the first input to the second output and the second input to the first output. In some embodiments, the inputs comprise a first input and a second input and the outputs comprise a first output and a second output, and the multiplexer is operable to connect (i) the first input to the first output and the second input to the second output during a first time period and (ii) the first input to the second output and the second input to the first output during a second time period.

(10) Some embodiments comprise connection pairs of column drivers, each connection pair comprising a first input, a second input, a first output, and a second output and during a first time period the multiplexer connects the first input to the first output and the second input to the second output of each connection pair and during a second time period the multiplexer connects the first input to the second output and the second input to the first output of each connection pair. In some embodiments, each of the connection pairs comprises a first input and a second input of the inputs and a first output and a second output of the outputs, and, for each of the connection pairs, the multiplexer is operable to connect (i) the first input to the first output and the second input to the second output during the first time period and (ii) the first input to the second output and the second input to the first output during a second time period.

(11) Some embodiments of the present disclosure comprise an integrated circuit substrate. The column drivers of the first and second connection pairs can be constructed on and spatially distributed over the integrated circuit substrate and can comprise a first connection pair and a second connection pair. In some embodiments, connection pairs comprise a first connection pair and a second connection pair and the column driver corresponding to the first connection pair and the column driver corresponding to the second connection pairs are constructed on and spatially distributed over the integrated circuit substrate. The column drivers can comprise a first column driver connected to the first input of the first connection pair, a second column driver connected to the second input of the first connection pair, a third column driver connected to the first input of the second connection pair, and a fourth column driver connected to the second input of the second connection pair. The third column driver can be spatially disposed between the first column driver and the second cluster column driver, the fourth column driver can be spatially disposed between the first column driver and the second column driver, or both the third column driver and the fourth column driver can be spatially disposed between the first column driver and the second column driver.

(12) In some embodiments, the first time period has a first temporal duration, the second time period has a second temporal duration, and the first temporal duration and the second temporal duration are equal so that the first and second time periods have an equal temporal duration. In some embodiments, the first time period has a first temporal duration, the second time period has a second temporal duration, and the first temporal duration and the second temporal duration are not equal so that the first and second time periods have different temporal durations.
(13) According to some embodiments of the present disclosure, components include light emitters (e.g., each component is a pixel), for example light-emitting diodes such as inorganic light-emitting diodes or inorganic micro-light-emitting diodes. Each of the inorganic micro-light-emitting-diodes can have a length and a width each no greater than one hundred microns (e.g., no greater than fifty, twenty, ten, or five microns) and a thickness no greater than 50 microns (e.g., no greater than twenty, ten, five, two, or one micron).
(14) The multiple columns of components can comprise a first column of light emitters (e.g., comprised in pixels in the column) having a first average luminance and a second column of light emitters (e.g., comprised in pixels in the column) having a second average luminance that is different from the first average luminance and a ratio of the first temporal duration to the second temporal duration can depend on a ratio of the first average luminance to the second average luminance. In some embodiments, a first column of light emitters (e.g., comprised in pixels in the column) having a first average luminance is connected to one of the first output and the second output and a second column of light emitters (e.g., comprised in pixels in the column) having a second average luminance that is different from the first average luminance is connected to the other of the first output and the second output, and wherein a ratio of a temporal duration of the first time period to a temporal duration of the second time period depends on a ratio of the first average luminance to the second average luminance.
(15) In some embodiments, the inputs comprise N inputs, the outputs comprise N outputs and during each of N time periods each of the N inputs is uniquely connected to each of the N outputs in response to the multiplexer control signal and the connections between the N inputs and the N outputs are different during each of the N time periods. Some embodiments comprise one or more groups of M column drivers, M<=N. Each of the groups of M column drivers can provide drive signals to M inputs of the column multiplexer. During each of M time periods the column multiplexer uniquely connects each of the M inputs to each of the M outputs for each group and the connection between the M inputs and the M outputs for each of the M time periods is different. Each of the inputs can be a member of a group and each of the outputs can be a member of a group.
(16) The column drivers are constructed on and spatially distributed over the integrated circuit substrate. Each group of M column drivers comprises a column driver connected to each of the M inputs and one or more column drivers of a group are disposed spatially between the column drivers of another, different group.
(17) In embodiments of the present disclosure, the N time periods have an equal temporal duration. In embodiments of the present disclosure, at least some of the N time periods have different temporal durations. In some embodiments, the multiple columns of components comprise N columns of light emitters (e.g., comprised in pixels in the columns), each of the columns of light emitters have an average luminance, and the temporal duration of each of the N time periods depends on the relative average luminance of the N columns of light emitters.
(18) Embodiments of the present disclosure comprise an integrated circuit substrate having variable epitaxy. The performance of circuits made in the variable epitaxy can vary so that at least some of the column drivers have at least some different electrical characteristics. The column drivers are disposed in the integrated circuit and at least some different electrical characteristics of the column drivers are dependent on the spatial location of the corresponding column drivers within the integrated circuit.
(19) In some embodiments, a passive-matrix display comprises components that each include one

or more light emitters, for example each component is a pixel with one light emitter or with multiple light emitters (e.g., a set of red, green, and blue emitters). In some embodiments, the light emitters are light-emitting diodes. The light-emitting diodes can be inorganic micro-light-emitting-diodes and each of the inorganic micro-light-emitting-diodes can have a length and a width each no greater than one hundred microns (e.g., no greater than fifty, twenty, ten, or five microns) and a thickness no greater than 50 microns (e.g., no greater than twenty, ten, five, two, or one micron).
(20) A passive-matrix display can comprise two or more columns of pixels and a cluster column driver providing a drive signal to each column of the two or more columns of pixels. Each of the column drivers can be operable to drive each column of pixels of the two or more columns of pixels with a drive signal during a frame period.
(21) Each of the pixels can comprise one or more inorganic micro-light-emitting-diodes, for example three LEDs in a color pixel. Each of the inorganic micro-light-emitting-diodes can have a length and a width each no greater than 200 microns, no greater than 100 microns, no greater than 50 microns, no greater than 20 microns, no greater than 215 microns, or no greater than 10 microns.
(22) According to embodiments of the present disclosure, a method for controlling components that are disposed in columns comprises providing a controller that comprises column drivers, one for each of the columns, and a multiplexer comprising outputs and inputs, each of the inputs connected to one of the column drivers and each of the outputs connected to one of the columns of the components, uniquely connecting each of the inputs to one of the outputs in response to a multiplexer control signal and, for each of the column drivers, providing a drive signal from the column driver to a respective one of the columns of components. The inputs can comprise a first input and a second input and the outputs can comprise a first output and a second output. The method can comprise connecting the first input to the first output and the second input to the second output during a first time period and subsequently connecting the first input to the second output and the second input to the first output during a second time period.
(23) In some embodiments, the first time period has a first temporal duration, the second time period has a second temporal duration, and the first temporal duration and the second temporal duration are equal. In some embodiments, the first time period has a first temporal duration, the second time period has a second temporal duration, and the first temporal duration and the second temporal duration are not equal.
(24) In some embodiments, a first column of light emitters having a first average luminance is connected to one of the first output and the second output and a second column of light emitters having a second average luminance that is different from the first average luminance is connected to the other of the first output and the second output, and a ratio of a temporal duration of the first time period to a temporal duration of the second time period is based on a ratio of the first average luminance to the second average luminance.
(25) In some embodiments, the inputs and the outputs are together grouped as connection pairs, each of the connection pairs comprises a first input and a second input of the inputs and a first output and a second output of the outputs, and methods of the present disclosure can comprise, for each of the connection pairs, (i) connecting the first input to the first output and the second input to the second output during the first time period and (ii) subsequently connecting the first input to the second output and the second input to the first output during a second time period.
(26) In some embodiments, the column drivers are native to and spatially distributed over an integrated circuit substrate.
(27) Methods of the present disclosure comprise connecting different ones of the column drivers, one at a time, to one of the columns of components with the multiplexer and providing a drive signal from each of the different ones of the column drivers to the components in the one of the columns when connected by the multiplexer. The period of time can be a frame period. The different ones of the column drivers can comprise each of the column drivers.

(28) Some embodiments comprise simultaneously connecting adjacent ones of the column drivers to non-adjacent ones of the columns of the components with the multiplexer. Some embodiments comprise providing drive signals from the adjacent ones of the column drivers to the non-adjacent ones of the columns of the components while simultaneously connected. Some embodiments comprise simultaneously connecting non-adjacent ones of the column drivers to adjacent ones of the columns of the components with the multiplexer. Some embodiments comprise providing drive signals from the non-adjacent ones of the column drivers to the adjacent ones of the columns of the components while simultaneously connected.
(29) In some embodiments, the inputs comprise N inputs, the outputs comprise N outputs and methods of the present disclosure comprise, during each of N time periods, uniquely connecting each of the N inputs to each of the N outputs in response to a multiplexer control signal with different connections between the N inputs and the N outputs during each of the N time periods. The N time periods can have an equal temporal duration. In some embodiments, at least some of the N time periods have different temporal durations from each other.
(30) In some embodiments, the columns of components comprise N columns of light emitters, each of the columns of light emitters having an average luminance, and a temporal duration of each of the N time periods is based on a relative average luminance of the N columns of light emitters. In some embodiments, the components are also disposed in rows thereby defining a two dimensional array, and methods of the present disclosure comprise providing row select signals sequentially to the rows of the components and operating the components in each of the rows when that row is selected by one of the row select signals.
(31) The components can be light emitters and operating the components can comprise emitting light from the light emitters. The components can be comprised in one cluster of a plurality of clusters in a device.
(32) According to embodiments of the present disclosure, the device is a display.
(33) Embodiments and methods of the present disclosure provide passive display control methods, devices, and structures that provide improved control uniformity.

Description

BRIEF DESCRIPTION OF THE DRAWINGS
(1) The foregoing and other objects, aspects, features, and advantages of the present disclosure will become more apparent and better understood by referring to the following description taken in conjunction with the accompanying drawings, in which:
(2) FIG. **1** is a schematic of a display according to illustrative embodiments of the present disclosure;
(3) FIG. **2** is a schematic of a pixel cluster in a display comprising light-emitting diodes in a passive-matrix configuration according to illustrative embodiments of the present disclosure;
(4) FIG. **3** is a schematic of a cluster controller with multiplexed column drivers and a row of light-emitting diodes according to illustrative embodiments of the present disclosure;
(5) FIG. **4** is a schematic of a cluster controller with multiplexed column drivers and a row of light-emitting diodes according to illustrative embodiments of the present disclosure;
(6) FIG. **5**A is a table showing timing for a two-column multiplexed column driver circuit according to illustrative embodiments of the present disclosure;
(7) FIG. **5**B is a table showing input and output connections for two-column column-driver modes according to illustrative embodiments of the present disclosure;
(8) FIG. **6**A is a logic circuit for the two-column column-driver modes of FIGS. **5**A and according to illustrative embodiments of the present disclosure;
(9) FIG. **6**B is a schematic circuit diagram showing input and output connections for two-column

column-driver modes of FIGS. **5**A and **5**B and the logic circuit of FIG. **6**A according to illustrative embodiments of the present disclosure;
(10) FIGS. **7**A-**7**C illustrate relative spatial locations of cluster column drivers in connection pairs according to illustrative embodiments of the present disclosure;
(11) FIG. **8**A is a table showing timing for a four-column multiplexed column driver circuit according to illustrative embodiments of the present disclosure;
(12) FIG. **8**B is a table showing input and output connections for four-column column-driver modes according to illustrative embodiments of the present disclosure; and
(13) FIG. **9** is a logic circuit for four-column column-driver modes of FIGS. **8**A and **8**B according to illustrative embodiments of the present disclosure.
(14) Features and advantages of the present disclosure will become more apparent from the detailed description set forth below when taken in conjunction with the drawings, in which like reference characters identify corresponding elements throughout. In the drawings, like reference numbers generally indicate identical, functionally similar, and/or structurally similar elements. The figures are not drawn to scale since the variation in size of various elements in the Figures is too great to permit depiction to scale.

DETAILED DESCRIPTION OF CERTAIN EMBODIMENTS

(15) Integrated circuits, for example integrated circuits used to construct driver circuits for passive-matrix control of rows or columns of light emitters in a display, are often formed in a semiconductor epitaxy—a layer of semiconductor material disposed on a crystalline substrate in which the passive-matrix driver circuits are formed. Ideally, the epitaxy would be perfect, without crystal defects, particulate contamination, or variations in thickness or doping. In manufacturing practice, however, the epitaxy varies over the extent of a semiconductor wafer. The epitaxial variation affects the performance of circuits photolithographically formed in the epitaxy, which can therefore be dependent on the spatial location of the circuit on the semiconductor wafer. For example, circuits formed in different portions of a semiconductor wafer can have different speeds, different efficiencies, different conductivities, different switching voltages, and so on. In particular, driver circuits made in different areas of an integrated circuit can drive different amounts of current, different voltages, different switching voltages, or at different frequencies even when controlled with the same control signals. In a passive-matrix display with a column-driver circuit for each column of light emitters (e.g., inorganic light-emitting diodes), the variation in performance of column-driver circuit formed in different spatial portions of epitaxy in an integrated circuit can cause visual defects and non-uniformities in the columns of light emitters in the display.
(16) Embodiments of the present disclosure provide, inter alia, passive-matrix display control methods and architectures that reduce performance non-uniformity in passive-matrix displays due to variation in driver circuit epitaxy in an integrated circuit. The components can be pixels that comprise one or more light emitters. The one or more light emitters can be one or more inorganic light-emitting diodes, for example one or more micro-light-emitting diodes. A driver circuit responds to control signals to provide a current or a voltage for a specified period of time to a wire connected to one or more pixels in a row or column. The control signals can be analog signals, e.g., controlling a variable current or voltage for the specified period of time, or a digital signal, e.g., providing a fixed current or voltage or no voltage or current for the specified period of time, for example data signals such as pixel data signals, timing signals, or pulse-width modulation signals. Components in a column (e.g., and also in a row) can include one or more light emitters, for example can be pixels that each include one light emitter or multiple light emitters (e.g., a set of red, green, and blue emitters). Components can be disposed in an array (e.g., regular array) having columns and rows.
(17) Embodiments of the present disclosure are described with respect to column drivers and columns of components but the choice of which direction is the “column” direction is arbitrary. Therefore, reference herein to columns and/or column drivers does not necessarily imply any

particular orientation (e.g., vertical); columns can be oriented left to right or right to left, for example. Column drivers can be display column drivers that drive entire columns of components (e.g., pixels or light emitters) (e.g., in a display), or column drivers can be cluster column drivers that drive entire columns of components (e.g., pixels or light emitters) in a cluster of a component array (e.g., in a display). That is, description of column drivers as driving Cluster column drivers are considered as particular embodiments of column drivers.

(18) According to some embodiments of the present disclosure and as illustrated in FIG. **1**, display **50**, e.g., a flat-panel display **50**, comprises a display substrate **10** and pixel clusters **20** distributed in an array comprising rows and columns of pixel clusters **20** over display substrate **10**. Pixel clusters **20** can be, but are not necessarily, spatially separate and non-overlapping so that nothing in a pixel cluster **20** is disposed spatially within an area of display substrate **10** that includes another, different pixel cluster **20**. Display **50** can be controlled by a display controller **40** and can be connected to, control, or comprise a display column controller **40**C and a display row controller **40**R and can provide display control signals to the array of pixel clusters **20**. Display column controller **40**C can provide display column signals (e.g., display column-data signals) to pixel clusters **20** through display column wires **42**C. Each display column wire **42**C uniquely connects to each pixel cluster **20** in a column of pixel clusters **20** in display **50** and uniquely provides control signals to the connected column. Display row controller **40**R can provide display row signals (e.g., display row-select signals) to pixel clusters **20** through display row wires **42**R. Each display row wire **42**R uniquely connects to each pixel cluster **20** in a row of pixel clusters **20** in display **50** and uniquely provides control signals to the connected row. Display controller **40**, display row controller **40**R, and display column controller **40**C can provide active-matrix control to pixel clusters **20**.

(19) FIG. **1** illustrates a display controller **40** controlling an array of pixel clusters **20** with active-matrix control signals such as row-select signals provided on display row wires **42**R and column-data signals provided on display column wires **42**C, for example using display row controller **40**R and display column controller **40**C. Although the Figures illustrate such an active-matrix control method and structure for pixel clusters **20**, embodiments of the present disclosure are not limited to such a control technique. For example, pixel clusters **20** can be controlled using active-matrix signals provided through token-passing structures or direct connection to each pixel cluster **20**, for example as disclosed in U.S. patent application Ser. No. 17/074,596, filed on Oct. 19, 2020, U.S. patent application Ser. No. 17/074,600, filed on Oct. 19, 2020, and U.S. patent application Ser. No. 17/553,304, filed on Dec. 16, 2021, the disclosure of each of which is hereby incorporated by reference herein in its entirety.

(20) As shown in FIG. **2**, each pixel cluster **20** can comprise an array **12** of components **14** (e.g., pixels **14**) controlled by cluster controller **22**. Pixels **14** can comprise a light emitter **16** (e.g., a light-emitting diode, such as an inorganic micro-light-emitting diode, or multiple light emitters **16** (e.g., multiple light emitters **16** that emit different colors of light). Light emitters **16** in pixel clusters **20** can define an array **12** in a display area of display substrate **10**. Light emitters **16** can be connected by cluster row wires **22**R and cluster column wires **22**C in pixel cluster **20** on display substrate **10** or on a separate cluster substrate (not shown). Pixels **14** can comprise a red light emitter emitting red light, a green light emitter emitting green light, and a blue light emitter emitting blue light when provided with pixel data and suitable control, power, and ground signals from cluster controller **22** forming a picture element or pixel **14** in pixel clusters **20** of display **50**. Cluster controller **22** can comprise, control, or is connected to cluster row controller **20**R and cluster column controller **20**C that provide control signals (timing signals or pixel data) to cluster row wires **22**R and cluster column wires **22**C and to pixels **14**. If pixels **14** comprise red, green, and blue light emitters **16**, each color of light emitter **16** can be connected to separate cluster row wires **22**R and cluster column wires **22**C connected to cluster row controller **20**R and cluster column controller **20**C. Pixel data can specify the light output from pixels **14** with digital values, for example using pulse-width modulation (PWM), or with analog values such as variable currents or

voltages. Pixels **14** in each pixel cluster **20** can be adjacent so that no pixel **14** from any other pixel cluster **20** is spatially disposed between pixels **14** in pixel cluster **20**. Pixel clusters **20** can be arranged with pixels **14** disposed in a regular array **12** with a cluster controller **22** disposed between rows or columns of pixels **14** in a pixel cluster **20** or between pixel clusters **20**. Such an arrangement of pixel clusters **20**, light emitters **16**, and cluster controllers **22** has been successfully laid out for a display **50** on a display substrate **10**.

(21) Embodiments of the present disclosure can also be applied to cluster row controllers **20**R or display row controllers **40**R where the drive signals vary according to the spatial arrangement of cluster row controllers **20**R or display row controllers **40**R in an integrated circuit, for example integrated circuits formed in a crystalline semiconductor (e.g., silicon) substrate. As will be appreciated by those knowledgeable in the art, row and column designations are arbitrary and can be exchanged.

(22) FIG. **2** illustrates a cluster controller **22** controlling an array **12** of pixels **14** in each pixel cluster **20** with passive-matrix control signals provided on cluster row wires **22**R and cluster column wires **22**C. Thus, in some embodiments, display controller **40** provides active-matrix control to pixel clusters **20** and pixel clusters **20** provide passive-matrix control to pixels **14** (e.g., light emitters **16** such as inorganic micro-light-emitting diodes). In some embodiments, FIG. **2** can illustrate an entire passive-matrix display **50** without separately controlled pixels clusters **20** so that cluster controller **22**, cluster column controller **20**C, cluster row controller **20**R, cluster column wires **22**C, and cluster row wires **22**R are equivalently display controller **40**, display column controller **40**C, display row controller **40**R, display column wires **42**C, and display row wires **42**R, respectively. Thus, embodiments of the present disclosure can be applied to entire displays **50** without pixel clusters **20** rather than to pixel clusters **20** within a display **50**.

(23) FIG. **3** illustrates embodiments of passive-matrix controllers of the present disclosure for both a pixel cluster **20** and display **50**. Pixel cluster **20** includes a cluster controller **22** that can comprise cluster column controller **20**C as well as cluster row controller **20**R for controlling an array **12** of pixels **14** (e.g., light emitters **16**) connected in rows and columns by cluster row wires **22**R and cluster column wires **22**C, respectively. (For brevity, only one row of light emitters **16** is shown in array **12** of light emitters **16**. Embodiments of the present disclosure are illustrated with a four-by-four array **12** of light emitters **16**, but embodiments are not limited to such and can comprise any array **12** size, generally with at least two columns of light emitters **16**.) Cluster controller **22** can, but does not necessarily, comprise a column shift register **28** for providing pixel data received from cluster controller **22** to each cluster column wire **22**C specifying the desired luminance of each light emitter **16** in a row of light emitters **16** selected by cluster row controller **20**R on cluster row wires **22**R. Column shift register **28** can comprise a digital serial shift register for shifting digital pixel data or can comprise an analog serial shift register for shifting analog pixel data comprising capacitors for storing charge (e.g., a bucket brigade). The pixel data for each column of light emitters **16** are provided to cluster column drivers **24** that transform the pixel data to a pixel control signal input to column multiplexer **26**, for example a current or voltage, labeled I.sub.0 to I.sub.N for an (N+1)-column array **12** of light emitters **16**. The multiplexer input signals I are then multiplexed by column multiplexer **26** in response to multiplexer control signal M from cluster controller **22** to corresponding multiplexer output signals O.sub.0 to O.sub.N on cluster column wires **22**C that drive light emitters **16** in each column of a row of light emitters **16** selected by cluster row controller **20**R on cluster row wires **22**R to emit light in response to the pixel data provided by cluster controller **22**. A similar column multiplexer **26** can be provided to supply corresponding pixel data to each drive circuit **24** in response to mode M, as shown in FIG. **3**.

(24) FIG. **4** is a more detailed illustration of the circuit of FIG. **3**. As shown in FIG. **4**, column multiplexer **26** can comprise a cross-point switch that connects multiplexer input signals I.sub.0 to I.sub.N to multiplexer output signals O.sub.0 to O.sub.N, for example with a transistor switch **30**. In embodiments of the present disclosure, the cross-point switch does not need to connect every

multiplexer input I to every multiplexer output O depending on multiplexer control signal M but only needs to uniquely connect each multiplexer input I to a multiplexer output O so that no multiplexer output O is connected to more than one multiplexer input I at a time. (Pixel cluster **20** as illustrated in FIGS. **3** and **4** is a simplified schematic and does not necessarily include all of the logic circuits used to actually implement the desired functionality; those of ordinary skill in the art will understand how to implement any such logic circuits.)

(25) In embodiments of the present disclosure, the different cluster column drivers **24** can be constructed in an integrated circuit that has spatially variable epitaxy so that the different cluster column drivers **24**, made in different spatial portions of the integrated circuit, have different performance characteristics. For example, if cluster column drivers **24** are disposed in the integrated circuit in a row so that cluster column driver **24** for I.sub.0 is spatially farthest from cluster column driver **24** for I.sub.N, those cluster column drivers **24** I.sub.0 and I.sub.N can be the most different in performance. According to embodiments of the present disclosure, those differences can be mitigated by using each cluster column driver **24** to drive each cluster column wire **22**C at a different time with the same pixel data. If each cluster column wire **22**C is driven for an (e.g., equal) amount of time with the same signal for each cluster column driver **24**, the output on each cluster column wire **22**C will be the temporal average of the output from each cluster column driver **24**. If the amounts of time are small enough, a human observer will not observe any temporal flickering due to the different performances of each cluster column driver **24** in a column of pixels **14**.

(26) For example, and as illustrated in FIG. **5**A for a two-column array **12** of light emitters **16**, a first image frame (a first image comprising pixel data) is displayed for a frame period of time F.sub.0 and a second image frame (second image comprising pixel data) is displayed for a frame period of time F.sub.1. A frame period F is a temporal period during which display **50** (or a cluster **20**) is intended to display a single, unchanging image. Each frame period of time F is divided into a number of temporal periods T (e.g., temporal periods T.sub.0 and T.sub.1) corresponding to the number of columns of light emitters **16**. Frame periods F.sub.0 and F.sub.1 can be equal. As shown in FIGS. **5**A and **5**B, during temporal period T.sub.0 column multiplexer **26** operates in Mode **0** (M.sub.0) to connect I.sub.0 to O.sub.0 and I.sub.1 to O.sub.1. During temporal period T.sub.1 column multiplexer **26** operates in Mode **0** (M.sub.0) to connect I.sub.0 to O.sub.1 and I.sub.1 to O.sub.0. The mode signals M.sub.0 to M.sub.N-1 (where N=2, the number of columns in this example) are collectively referred to as multiplexer control signal M. Thus, according to embodiments of the present disclosure, a passive-matrix controller can comprise column multiplexer **26** having first input I.sub.0, second input I.sub.1, first output O.sub.0, and second output O.sub.1. During first time temporal period T.sub.0, column multiplexer **26** in mode M.sub.0 connects first input I.sub.0 to first output O.sub.0 and second input I.sub.1 to second output O.sub.1. During second time temporal period T.sub.1, column multiplexer **26** in mode M.sub.1 connects first input I.sub.0 to second output O.sub.1 and second input I.sub.1 to first output O.sub.0.

(27) During each frame period F, each column of light emitters **16** can be driven for one half of frame period F with a first cluster column driver **24** and the other half of frame period F with a second cluster column driver **24** so that any performance differences of the cluster column drivers **24** are averaged out for each column of light emitters **16** over frame period F. If both columns of light emitters **16** are driven with the same control signal, the light output from the columns of light emitters **16** is the same. A suitable frame period can be 1/60 second, or 1/120 second so that T.sub.0 and T.sub.1 are 1/120 second or 1/240 second, respectively. Such frame rates can be sufficient to avoid visible flickering due to differences in cluster column drivers **24** performance.

(28) FIG. **6**A is a logic diagram illustrating implementations of the embodiments of FIGS. **5**A and **5**B. As shown in FIG. **6**A, a multiplexer (mode) control signal M selects between mode **0** and mode **1** of FIG. **5**B using AND gates. When M is positive, I.sub.0 is connected to O.sub.0 and I.sub.1 is

connected to O.sub.1. When M is negative, I.sub.0 is connected to O.sub.1 and I.sub.1 is connected to O.sub.0. Although shown as AND gates (logic gates), the input signals can be analog signals that are switched using an analog switch with a high-impedance output (a tri-state output), for example as shown in FIG. **6**B. FIG. **6**B illustrates two current sources **32** (or alternatively voltage sources) labeled V.sub.0, V.sub.1) each controlled by a different pixel data signal. Each of P.sub.0 and P.sub.1 are driven with a corresponding source V.sub.0, V.sub.1. When M is positive (e.g., M.sub.0), for example during T.sub.0 of a frame period, V.sub.0 (in response to pixel data for pixel P.sub.0) is switched through a transistor switch **30** to P.sub.0 and V.sub.1 (in response to pixel data for pixel P.sub.1) is switched through a transistor switch **30** to P.sub.1. (Pixels P.sub.0, P.sub.1 include light emitters **16**.) When M is negative (e.g., M.sub.1), for example during T.sub.1 of a frame period, V.sub.0 (in response to pixel data for pixel P.sub.1) is switched through a transistor switch **30** to P.sub.1 and V.sub.1 (in response to pixel data for pixel P.sub.0) is switched through a transistor switch **30** to P.sub.0. Thus, the luminance from each pixel P.sub.0, P.sub.1 for the entire frame period is the average of the driving signal from V.sub.0 and V.sub.1 so that any differences in performance (non-uniformity) of V.sub.0 and V.sub.1 are mitigated or entirely removed for each of pixels P.sub.0, P.sub.1.

(29) In some embodiments of the present disclosure, cluster column drivers **24** are spatially distributed over an epitaxial area, for example a portion of an integrated circuit. Columns of light emitters **16** can be connection pairs driven by corresponding cluster column drivers **24**. Each connection pair can comprise a first input, a second input, a first output, and a second output and (i) during the first time period the multiplexer connects the first input to the first output and the second input to the second output of each connection pair and (ii) during a second time period the multiplexer connects the first input to the second output and the second input to the first output of each connection pair, for example as discussed with respect to FIGS. **5**A-**6**B. In some embodiments of the present disclosure, the spatial location of a cluster column driver **24** in a first connection pair is disposed between the spatial locations of a cluster column driver **24** in a second connection pair so that at least one cluster column driver **24** of the first connection pair is interdigitated between the cluster column drivers **24** of the second connection pair. Assuming that the performance variation of cluster column drivers **24** is monotonic, the average performance of cluster column drivers **24** of the first connection pair is closer to the average performance of cluster column drivers **24** of the second connection pair than would be the case if the cluster column drivers **24** of the first and second connection pairs were not interdigitated. For example and as illustrated in FIGS. **7**A-**7**C, connection pair A has cluster column drivers **24** A**0** and A**1** and connection pair B has cluster column drivers **24** B**0** and B**1** disposed on variable-performance epitaxy **25** in the spatial order shown. Arbitrarily assuming that the spatial variation in performance varies monotonically from 2 to 3 to 4 to 5 in the four locations of epitaxy **25**, as shown in FIG. **7**A connection pair A will have an average performance over a frame period of 2.5 (equal to (2+3)/2) and connection pair B will have an average performance over the frame period of 4.5 (equal to (4+5)/2) for an average cluster column driver **24** performance difference between the connection pairs A and B of 2. In contrast and as shown in FIG. **7**B with a cluster column driver **24** of connection pair B disposed between the cluster column drivers **24** of connection pair A, the average performance of connection pair A will be 3 (equal to (2+4)/2) and the average performance of connection pair B will be 4 (equal to (3+5)/2) so that the difference is 1, a value less than 2 and therefore providing better performance uniformity. As shown in FIG. **7**C with both cluster column drivers **74** of connection pair B disposed between the cluster column drivers **24** of connection pair A, the average performance of connection pair A will be 3.5 (equal to (2+5)/2) and the average performance of connection pair B will also be 3.5 (equal to (3+4)/2) so that the difference is zero so that the average performance of cluster column drivers **24** of the connection pairs is the same and the performance variation of the epitaxy **25** and cluster column drivers **24** in an integrated circuit is mitigated or reduced.

(30) Thus, according to embodiments of the present disclosure, a passive-matrix controller

comprises an integrated circuit substrate on which column drivers for at least two connection pairs are constructed and spatially distributed. A first connection pair comprises first and second cluster column drivers **24** disposed on the integrated circuit substrate and a second connection pair comprises third and fourth cluster column drivers **24** disposed on the integrated circuit substrate. The first cluster column driver **24** can be connected to the first input of the first connection pair and the second cluster column driver **24** can be connected to the second input of the first connection pair. The third cluster column driver **24** can be connected to the first input of the second connection pair and the fourth cluster column driver **24** can be connected to the second input of the second connection pair. The third cluster column driver **24** can be spatially disposed between the first column driver and the second column driver. In some embodiments, the third and fourth cluster column drivers **24** can be spatially disposed between the first cluster column driver **24** and the second cluster column driver **24**.

(31) In some embodiments, the first time period has a first temporal duration, the second time period has a second temporal duration, and the first temporal duration and the second temporal duration are equal. However, in some embodiments (e.g., as shown in FIG. **7**B), the average performance of different connection pairs (or more generally the average performance of different groups of cluster column drivers **24**) can be different. This difference can also be mitigated by controlling the relative duration of the time periods T within an image frame period F. For example, and corresponding to FIG. **7**B, if time periods corresponding to B**0** and A**1** are twice as long as the time periods corresponding to A**0** and B**1**, the average difference is 0.33 rather than 1. Thus, in some embodiments, the first temporal duration and the second temporal duration are not equal. In particular, if components **14** include light emitters **16** such as inorganic light-emitting diodes that emit light in response to control signals, a ratio of the temporal durations of the time periods can correspond to or depend upon the relative luminance of each column of light emitters **16**.

(32) The examples of FIGS. **8**A, **8**B, and **9** are embodiments of the present disclosure with four columns of light emitters **16** in a passive-matrix-controlled array **12**. As shown in FIGS. **8**A and **8**B, during each of sequential frame times F.sub.0 and F.sub.1, a passive-matrix cluster column controller **20**C (or display column controller **40**C) can control each of four light emitter **16** columns in each of four sequential time periods T with a different cluster column driver **24** and each of the four light emitter **16** columns is driven with a different cluster column driver **24** in each of the four sequential time periods T corresponding to the number of columns as illustrated with mode **0** (M.sub.0), mode **1** (M.sub.1), mode **2** (M.sub.2), and mode **3** (M.sub.3) to connect inputs I to outputs O as shown in FIG. **6**B for each of the modes M. Thus, according to methods of the present disclosure, a passive-matrix display **50** or portion of a display **50** (e.g., a pixel cluster **20** of pixels **14** in a display **50**) comprises two or more columns of pixels **14** driven by a corresponding two or more cluster column drivers **24** that controls (e.g., drives) each of the columns of pixels **14** with each of the two or more cluster column drivers **24** during a frame period.

(33) FIG. **8**A illustrates embodiments with a four-column array **12** of light emitters **16**, a first frame (first image comprising pixel data) is displayed for a frame period of time F.sub.0, and a second frame (second image comprising pixel data) is displayed for a frame period of time F.sub.1. Each frame period of time is divided into four equal sub-periods T.sub.0, T.sub.1, T.sub.2, and T.sub.3 corresponding to the number of columns of light emitters **16**. Frame periods F.sub.0 and F.sub.1 can be equal in temporal duration. As shown in FIGS. **6**A and **6**B, during T.sub.0 (Mode **0** or M.sub.0), a first column multiplexer **26** connects I.sub.0 to O.sub.0, I.sub.1 to O.sub.1, I.sub.2 to O.sub.2, and I.sub.3 to O.sub.3. During T.sub.1 (Mode **1** or M.sub.1), a second column multiplexer **26** connects I.sub.0 to O.sub.3, I.sub.1 to O.sub.0, I.sub.2 to O.sub.1, and I.sub.3 to O.sub.2. During T.sub.2 (Mode **2** or M.sub.2), a third column multiplexer **26** connects I.sub.0 to O.sub.2, I.sub.1 to O.sub.3, I.sub.2 to O.sub.0, and I.sub.3 to O.sub.1. During T.sub.3 (Mode **3** or M.sub.3), and a fourth column multiplexer **26** connects I.sub.0 to O.sub.1, I.sub.1 to O.sub.2, I.sub.2 to O.sub.3, and I.sub.3 to O.sub.0. The mode signals M.sub.0-4 are collectively multiplexer control

signal M. Thus, over each frame period F, each column of light emitters **16** is driven for one quarter of the frame period F with each cluster column driver **24** so that the columns of light emitters **16** will emit the same amount of light over the entire frame period F if controlled with the same control signal. A suitable frame period F can be 1/60 second, or 1/120 second so that T.sub.0, T.sub.1, T.sub.2, and T.sub.3 are 1/240 second or 1/480 second, respectively. Such frame rates can be sufficient to avoid visible flickering due to differences in cluster column drivers **24** performance.

(34) FIG. **9** is a logic diagram illustrating implementations of the embodiments of FIGS. **8**A and **8**B for a four-column implementation. In such embodiments, two bits are needed to encode the mode value M and can be demultiplexed into four control (mode) signals M.sub.0, M.sub.1, M.sub.2, and M.sub.3. Each of M.sub.0, M.sub.1, M.sub.2, and M.sub.3 then selects from among I.sub.0, I.sub.1, I.sub.2, and I.sub.3 and switches each of I.sub.0, I.sub.1, I.sub.2, and I.sub.3 to the appropriate output O.sub.0, O.sub.1, O.sub.2, and O.sub.3. As shown in FIG. **8**B. Mode signal M can be generated by a two-bit counter, for example driven by a clock with a period one quarter of the frame period and synchronized with the frame period.

(35) Embodiments of the present disclosure are not limited to two or four columns and can comprise any number of columns of light-emitters no less than two, for example six, seven, eight, nine, ten, or twelve. More generally, column multiplexer **26** can comprise N inputs I and N outputs O corresponding to N columns. During each of N time periods each of the N inputs I is uniquely connected to each of the N outputs O in response to multiplexer control signal M and the connections between the N inputs I and the N outputs O are different during each of the N time periods. Where the inputs I and outputs are grouped (e.g., into connection pairs) and each of the groups comprises M inputs I and M outputs O, where M<=N, during each of M time periods the column multiplexer **26** uniquely connects each of the M inputs I to each of the M outputs O for each group and the connection between the M inputs I and the M outputs O for each time period T is different. Each of the inputs I can be a member of a group and each of the outputs O can be a member of a group. Some embodiments comprise an integrated circuit substrate or epitaxy **25**, cluster column drivers **24** are constructed on and spatially distributed over the integrated circuit substrate or epitaxy **25**, each group comprises a cluster column driver **24** connected to each of the M inputs I, and one or more cluster column drivers **24** of a group are disposed spatially between cluster column drivers **24** of another, different group (e.g., as shown in FIGS. **7**B and **7**C where M=2). The N time periods can have an equal temporal duration or different temporal durations. Different temporal durations can depend on different average cluster column driver **24** performance for the different groups. For example, if components **14** include light emitters **16**, each of the columns of light emitters **16** can have an average luminance, and the temporal duration of each of the N time periods can depend on the relative average luminance of the N columns of light emitters **16**.

(36) Generally, a passive-matrix display **50** or portions of a passive-matrix display **50** (e.g., pixel clusters **20**) can comprise two or more columns of pixels **14** and a cluster column driver **24** providing a separate and individual drive signal to each column of the two or more columns of pixels **14**. Each of cluster column drivers **24** can be operable to separately drive each column of pixels **14** of the two or more columns of pixels **14** with a drive signal during a frame period F. Because non-uniformity in cluster column drivers **24** is reduced, in some embodiments smaller or simpler circuits can be used to drive columns of light emitters **16**, thus increasing display **50** resolution.

(37) Display substrate **10** can be any useful substrate on which pixels **14**, cluster controllers **22**, display row wires **42**R, and display column wires **42**C can be suitably disposed, for example glass, plastic, resin, fiberglass, semiconductor, ceramic, quartz, sapphire, or other substrates found in the display or integrated circuit industries. Display substrate **10** can be flexible or rigid and can be substantially flat. Display column wires **42**C and display row wires **42**R can be wires (e.g., photolithographically defined electrical conductors such as metal lines) disposed on display

substrate **10** that conduct electrical current or voltage (e.g., control signals) from display column controller **40**C to columns of pixel clusters **20** or from display row controller **40**R to rows of pixel clusters Similarly, cluster column wires **22**C and cluster row wires **22**R can be wires (e.g., photolithographically defined electrical conductors such as metal lines) disposed on display substrate **10** or a separate and independent cluster substrate disposed on display substrate **10** that conduct electrical current or voltage (e.g., control signals) from cluster column controller **20**C to columns of pixels **14** or from cluster row controller **20**R to rows of pixels **14**.

(38) Display column controller **40**C can be, for example, an integrated circuit or thin-film-transistor circuit that provides control, timing (e.g., clocks) or data signals (e.g., column-data signals) through display column wires **42**C to columns of pixel clusters **20** to enable pixel clusters **20** to control light emitted by light emitters **16** in each pixel cluster **20** in flat-panel display **50**. Display column controller **40**C can comprise a single integrated circuit or can comprise multiple integrated circuits, e.g., electrically connected integrated circuits. The integrated circuit(s) can be micro-transfer printed as unpackaged dies and can comprise broken (e.g., fractured) or separated tether(s). Each display column wire **42**C can be electrically separate and optionally independently controlled from every other display column wire **42**C by display column controller **40**C.

(39) Display row controller **40**R can be, for example, an integrated circuit or thin-film-transistor circuit that provides control, timing (e.g., clocks) or data signals (e.g., row-select signals) through display row wires **42**R to rows of pixel clusters **20** to enable pixel clusters **20** to control light emitted by light emitters **16** in each pixel cluster **20** in flat-panel display **50**. Display row controller **40**R can comprise a single integrated circuit or can comprise multiple integrated circuits, e.g., electrically connected integrated circuits. The integrated circuit(s) can be micro-transfer printed as unpackaged dies and can comprise broken (e.g., fractured) or separated tether(s). Each display row wire **42**R can be electrically separate and optionally independently controlled from every other display row wire **42**R by display row controller **40**R.

(40) Cluster column controller **20**C can be, for example, an integrated circuit or thin-film-transistor circuit that provides control, timing (e.g., clocks) or data signals (e.g., column-data signals) through display column wires **42**C to columns of pixels **14** to enable light emitters **16** in each pixel cluster **20** in flat-panel display **50** to emit light. Cluster column controller **20**C can comprise a single integrated circuit or can comprise multiple integrated circuits, e.g., electrically connected integrated circuits. The integrated circuit(s) can be micro-transfer printed as unpackaged dies and can comprise fractured or separated tether(s). Each cluster column wire **22**C can be electrically separate and optionally independently controlled from every other cluster column wire **22**C by cluster column controller **20**C. At least some different electrical characteristics of cluster column drivers **24** can be dependent on the spatial location of the corresponding cluster column drivers **24** within the integrated circuit.

(41) Cluster row controller **20**R can be, for example, an integrated circuit or thin-film-transistor circuit that provides control, timing (e.g., clocks) or data signals (e.g., row-select signals) through cluster row wires **22**R to rows of pixels **14** to enable light emitters **16** in each pixel cluster **20** in flat-panel display **50** to emit light. Cluster row controller **20**R can comprise a single integrated circuit or can comprise multiple integrated circuits, e.g., electrically connected integrated circuits. The integrated circuit(s) can be micro-transfer printed as unpackaged dies and can comprise broken (e.g., fractured) or separated tether(s). Each cluster row wire **22**R can be electrically separate and optionally independently controlled from every other cluster row wire **22**R by cluster row controller **20**R.

(42) Cluster column driver **24** can comprise an integrated circuit or epitaxy **25**. Drive circuits suitable for driving columns of light emitters **16** (e.g., with variable current, variable voltage, or constant current for variable amounts of time) can be formed in epitaxy **25**. Current sources, voltage sources (e.g., as in a pulse-amplitude modulation circuit), and constant current sources with variable temporal control (e.g., as in a pulse-width modulation circuit) can comprise a transistor

circuit responsive to power, ground, and control signals.
(43) Array **12** of pixels **14** can be a completely regular array **12** (e.g., as shown in FIG. **1**) or can have rows or columns of pixels **14** that are offset from each other, so that rows or columns of pixels **14** are not disposed in a straight line and can, for example, form a zigzag line (not shown in the Figures) or, as another example, have non-uniform spacing(s).
(44) Light emitters **16** can comprise light-emitting diodes, e.g., inorganic light-emitting diodes such as horizontal inorganic light-emitting diodes or vertical inorganic light-emitting diodes. Inorganic light-emitting diodes can have a small area, for example having a length and a width each no greater than 20 microns, no greater than 50 microns, no greater than 100 microns, or no greater than 200 microns. Such small light emitters **16** leave additional area on display substrate **10** for more or larger wires, e.g., display column wires **42**C, display row wires **42**R, cluster column wires **22**C, cluster row wires **22**R, ground and power wires, or cluster controllers **22**. Cluster controllers **22** can be disposed between array **12** of light emitters **16** in different pixel clusters **20** or within array **12** of light emitters **16** in a pixel cluster **20**.
(45) Pixels **14** or light emitters **16** can be multiple integrated circuits and can be micro-transfer printed onto display substrate **10** together with cluster controller **22** or onto a cluster substrate and the cluster substrate micro-assembled (e.g., micro-transfer printed) onto display substrate **10**. The multiple integrated circuits can be small, unpackaged integrated circuits such as unpackaged dies interconnected with wires connected to contact pads on the integrated circuits, for example formed using photolithographic methods and materials. In some embodiments, the integrated circuits are made in or on a semiconductor wafer and have a semiconductor substrate.
(46) In some embodiments, red, green, and blue inorganic LEDs **14** are micro transfer printed to cluster substrates or display substrate **10** in one or more transfers and can comprise broken (e.g., fractured) or separated tethers as a consequence of micro-transfer printing. For a discussion of micro-transfer printing techniques that can be used or adapted for use in methods disclosed herein, see U.S. Pat. Nos. 8,722,458, 7,622,367 and 8,506,867, each of which is hereby incorporated by reference in its entirety. The transferred light emitters **16** are then interconnected, for example with conductive wires and optionally including connection pads and other electrical connection structures, to enable a controller (e.g., display controller **40** or cluster controller **22**) to electrically interact with light-controlling elements **14** to emit, or otherwise control, light.
(47) Display substrate **10** or a cluster substrate, or both, can include glass, resin, polymer, plastic, or metal. The cluster substrate can be a semiconductor substrate and one or more of cluster controller **22**, cluster column controller **20**C and cluster row controller **20**R can be formed in or on the cluster substrate (and thus are native to the cluster substrate). Semiconductor materials (for example doped or undoped silicon, GaAs, or GaN) and processes for making small integrated circuits are well known in the integrated circuit arts. Likewise, backplane substrates and means for interconnecting integrated circuit elements on the backplane are well known in the display and printed circuit board arts.
(48) In certain embodiments, display substrate **10** includes material, for example glass or plastic, different from a material in an integrated-circuit substrate, for example a semiconductor material, such as silicon or GaN for example. Light emitters **16** or cluster controllers **22** can be formed separately on separate semiconductor substrates, assembled onto cluster substrates to form pixel clusters **20** and then the assembled units are disposed (e.g., printed) on the surface of the display substrate **10**. In some embodiments, light emitters **16** can be formed separately on separate semiconductor substrates in or on which native cluster controller **22** circuits are formed, assembled onto cluster substrates to form pixel clusters **20** and then the assembled units are disposed (e.g., printed) on the surface of the display substrate **10**. This arrangement has the advantage that the integrated circuits or pixel clusters **20** can be separately tested on the cluster substrate and pixel clusters **20** accepted, repaired, or discarded before pixel clusters **20** are located on display substrate **10**, thus improving yields and reducing costs.

(49) In a method according to some embodiments of the present disclosure, integrated circuits are disposed on the display substrate **10** by micro transfer printing. In some methods, integrated circuits (or portions thereof) or light emitters **16** are disposed on a cluster substrate to form a heterogeneous pixel cluster **20** and pixel cluster **20** is disposed on display substrate **10** using compound micro-assembly structures and methods, for example as described in U.S. patent application Ser. No. 14/822,868 filed Aug. 10, 2015, entitled Compound Micro-Assembly Strategies and Devices. However, since pixel clusters **20** can be larger than the integrated circuits included therein, in some methods of the present disclosure, pixel clusters **20** are, or can be, disposed on display substrate **10** using pick-and-place methods found in the printed-circuit board industry, for example using vacuum grippers. Pixel clusters **20** can be interconnected on display substrate **10** using photolithographic methods and materials or printed circuit board methods and materials, for example.
(50) In some embodiments of the present disclosure, providing flat-panel display **50**, display substrate **10**, or pixel clusters **20** can include forming conductive wires (e.g., display row wires **42**R, display column wires **42**C, cluster row wires **22**R, and cluster column wires **22**C on a substrate (e.g., display substrate **10** or a cluster substrate) by using photolithographic and display substrate **10** processing techniques, for example photolithographic processes employing metal or metal oxide deposition using evaporation or sputtering, curable resin coatings (e.g. SU-8), positive or negative photo-resist coating, radiation (e.g. ultraviolet radiation) exposure through a patterned mask, and etching methods to form patterned metal structures, vias, insulating layers, and electrical interconnections. Inkjet and screen-printing deposition processes and materials can be used to form patterned conductors or other electrical elements. The electrical interconnections, or wires, can be fine interconnections, for example having a width of less than fifty microns, less than twenty microns, less than ten microns, less than five microns, less than two microns, or less than one micron. Such fine interconnections are useful for interconnecting micro-integrated circuits, for example as bare dies with contact pads and used with the cluster substrates. Alternatively or additionally, wires can include one or more crude lithography interconnections having a width from 2 μm to 2 μm, wherein each crude lithography interconnection electrically interconnects pixel clusters on display substrate **10**.
(51) In some embodiments, components **14** are operable to emit light, for example when component **14** includes a light emitter or is a pixel **14**. In some embodiments, components **14** have functionality other than light emission that is exhibited by operating components **14** using controller **20**.
(52) As is understood by those skilled in the art, the terms “over”, “under”, “above”, “below”, “beneath”, and “on” are relative terms and can be interchanged in reference to different orientations of the layers, elements, and substrates included in the present disclosure. For example, a first layer on a second layer, in some embodiments means a first layer directly on and in contact with a second layer. In other embodiments, a first layer on a second layer can include another layer there between.
(53) As is also understood by those skilled in the art, the terms “column” and “row”, “horizontal” and “vertical”, and “x” and “y” are arbitrary designations that can be interchanged (unless otherwise clear from context).
(54) Throughout the description, where apparatus and systems are described as having, including, or comprising specific components, or where processes and methods are described as having, including, or comprising specific steps, it is contemplated that, additionally, there are apparatus, and systems of the disclosed technology that consist essentially of, or consist of, the recited components, and that there are processes and methods according to the disclosed technology that consist essentially of, or consist of, the recited processing steps.
(55) It should be understood that the order of steps or order for performing certain action is immaterial so long as operability is maintained. Moreover, two or more steps or actions in some

circumstances can be conducted simultaneously. The disclosure has been described in detail with particular express reference to certain embodiments thereof, but it will be understood that variations and modifications can be effected within the spirit and scope of the following claims.
PARTS LIST
(56) F frame period I multiplexer input signal M multiplexer control signal/mode control signal O multiplexer output signal T temporal period **10** display substrate **12** array/passive-matrix array **14** pixel/component **16** light emitter **20** pixel cluster **20**C cluster column controller/passive-matrix controller **20**R cluster row controller **22** cluster controller **22**C cluster column wire **22**R cluster row wire **24** column driver/cluster column driver/driver circuit **25** epitaxy **26** column multiplexer **28** column shift register **30** transistor switch **32** current source **40** display controller **40**C display column controller **40**R display row controller **42**C display column wire **42**R display row wire **50** display

Claims

1. A passive-matrix controller for providing a signal to each column of columns of components with a respective individual column wire, wherein the passive-matrix controller is a column controller, each of the components comprises a light-emitting diode for emitting a color of light for a corresponding pixel in an image, and the light-emitting diode of each of the components in a column emit the same color of light, the column controller comprising: column drivers, each of the column drivers operable to provide a drive signal for one of the columns of components in response to a pixel control signal, wherein the column drivers are spatially distributed over an epitaxial area of semiconductor epitaxy in a spatial order; and a column multiplexer comprising (i) outputs O arranged in a spatial order and (ii) inputs I, each of the outputs O uniquely connectable to a respective column wire and each of the inputs I connected to one of the column drivers to receive the drive signal, wherein the column multiplexer is a cross-point switch operable to uniquely connect each of the inputs I to a different one of the outputs O in response to a multiplexer control signal provided by the column controller to provide the drive signal from a column driver of the column drivers to one of the outputs O to drive the light-emitting diode for one of the components to emit the color of light such that (i) the column driver is disposed in a different position in the spatial order of the column drivers relative to a position of the one of the outputs Q in the spatial order of the outputs Q of the column multiplexer and (ii) the position of the one of the outputs O corresponds to a position of the corresponding pixel in the image.
2. The passive-matrix controller of claim 1, wherein the multiplexer control signal is a digital signal.
3. The passive-matrix controller of claim 2, wherein the multiplexer control signal is a data signal, a timing signal, or a pulse-width modulation signal.
4. The passive-matrix controller of claim 1, wherein the inputs I comprise a first input and a second input and the outputs O comprise a first output and a second output, and wherein the column multiplexer is operable to connect (i) the first input to the first output and the second input to the second output during a first time period and (ii) the first input to the second output and the second input to the first output during a second time period.
5. The passive-matrix controller of claim 4, comprising connection pairs, each of the connection pairs comprising a first input and a second input of the inputs I and a first output and a second output of the outputs O, and wherein, for each of the connection pairs, the column multiplexer is operable to connect (i) the first input to the first output and the second input to the second output during the first time period and (ii) the first input to the second output and the second input to the first output during a second time period.
6. The passive-matrix controller of claim 5, comprising an integrated circuit substrate, wherein the connection pairs comprise a first connection pair and a second connection pair and the column

drivers corresponding to the first connection pair and the column drivers corresponding to the second connection pairs are constructed on and spatially distributed over the integrated circuit substrate, wherein the column drivers comprise a first column driver connected to the first input of the first connection pair, a second column driver connected to the second input of the first connection pair, a third column driver connected to the first input of the second connection pair, and a fourth column driver connected to the second input of the second connection pair, and wherein the third column driver is spatially disposed between the first column driver and the second column driver in the spatial order of the column drivers so that a column driver of the second connection pair is interdigitated with a column driver of the first connection pair.

7. The passive-matrix controller of claim 6, wherein the fourth column driver is spatially disposed between the first column driver and the second column driver in the spatial order of the column drivers.

8. The passive-matrix controller of claim 6, wherein the first connection pair corresponds to spatially adjacent columns of the columns of components and the second connection pair corresponds to spatially adjacent columns of the columns of components, the first connection pair spatially adjacent to the second connection pair.

9. The passive-matrix controller of claim 4, wherein the first time period has a first temporal duration, the second time period has a second temporal duration, and the first temporal duration and the second temporal duration are equal.

10. The passive-matrix controller of claim 4, wherein the first time period has a first temporal duration, the second time period has a second temporal duration, and the first temporal duration and the second temporal duration are not equal.

11. The passive-matrix controller of claim 4, wherein a first column of light emitters having a first average luminance in response to pixel data, the first column is connected to one of the first output and the second output, and a second column of light emitters having a second average luminance in response to the pixel data that is different from the first average luminance, the second column is connected to the other of the first output and the second output, and wherein a ratio of a temporal duration of the first time period to a temporal duration of the second time period depends on a ratio of the first average luminance to the second average luminance.

12. The passive-matrix controller of claim 1, wherein the inputs I comprise N inputs, the outputs O comprise N outputs and the passive-matrix controller is operable to, during each of N time periods, uniquely connect each of the N inputs to each of the N outputs in response to the multiplexer control signal with different connections between the N inputs and the N outputs during each of the N time periods.

13. The passive-matrix controller of claim 12, comprising groups of M column drivers of the column drivers, where $2<M\leq N$, wherein each of the groups of M column drivers is operable to provide drive signals to M ones of the inputs I, wherein the column multiplexer is operable to, during each of M time periods, uniquely connect each of the M inputs to each of the M outputs for each of the groups with different connections between the M inputs and the M outputs for each of the M time periods.

14. The passive-matrix controller of claim 13, wherein each of the inputs I is a member of one of the groups and each of the outputs O is a member of one of the groups.

15. The passive-matrix controller of claim 14, comprising an integrated circuit substrate that comprises semiconductor epitaxy, wherein the column drivers are constructed on and spatially distributed over the integrated circuit substrate, and wherein one or more column drivers of a first one of the groups are disposed spatially between the column drivers of another, different one of the groups.

16. The passive-matrix controller of claim 12, wherein the N time periods have an equal temporal duration.

17. The passive-matrix controller of claim 12, wherein at least some of the N time periods have

different temporal durations from each other.
18. The passive-matrix controller of claim 12, wherein the columns of components comprise N columns of light emitters, each of the columns of light emitters having an average luminance, and wherein a temporal duration of each of the N time periods depends on a relative average luminance of the N columns of light emitters.
19. The passive-matrix controller of claim 1, wherein at least some of the column drivers have at least one different electrical performance characteristic from other column drivers in response to same pixel data.
20. The passive-matrix controller of claim 19, comprising an integrated circuit, wherein the column drivers are disposed in the integrated circuit and wherein the at least one different electrical performance characteristic of the column drivers is dependent on spatial locations of the at least some column drivers within the integrated circuit.
21. The passive-matrix controller of claim 1, wherein the passive-matrix controller is a cluster controller operable to control a cluster comprising the columns of the components.
22. A passive-matrix device comprising: a passive-matrix controller according to claim 1; the columns of components; and the respective row wire for each of the outputs O, wherein each of the outputs O is connected to the respective row wire and the respective row wire is connected to its column of the columns of components.
23. The device of claim 22, wherein the components are pixels.
24. The device of claim 22, wherein each of the components comprises a light emitter.
25. The device of claim 22, wherein the device is a display.