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Holmes et al.

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(54) **TRANSPARENT MICROLED DISPLAY FOR VR HEADSETS**

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Related U.S. Application Data

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(51) **Int. Cl.**
G02B 27/01 (2006.01)
G02B 27/00 (2006.01)
(Continued)

(52) **U.S. Cl.**
CPC ***G02B 27/0172*** (2013.01); ***G02B 27/0093*** (2013.01); ***G06F 3/013*** (2013.01); ***H01L 23/5387*** (2013.01); ***H01L 25/0753*** (2013.01); ***H05B 45/30*** (2020.01); ***H10H 20/8506*** (2025.01); ***H10H 20/852*** (2025.01); ***H10H 20/853*** (2025.01); ***H10H 20/856*** (2025.01); ***H10H 20/857*** (2025.01); ***H10H 29/142*** (2025.01); *G02B 27/0101* (2013.01); *G02B 2027/0112* (2013.01);
(Continued)

(58) **Field of Classification Search**
CPC H02B 27/0172; H02B 27/0093; H02B 27/017; G02B 2027/0118; G06F 3/013; G06F 3/011; H01L 25/0753
See application file for complete search history.

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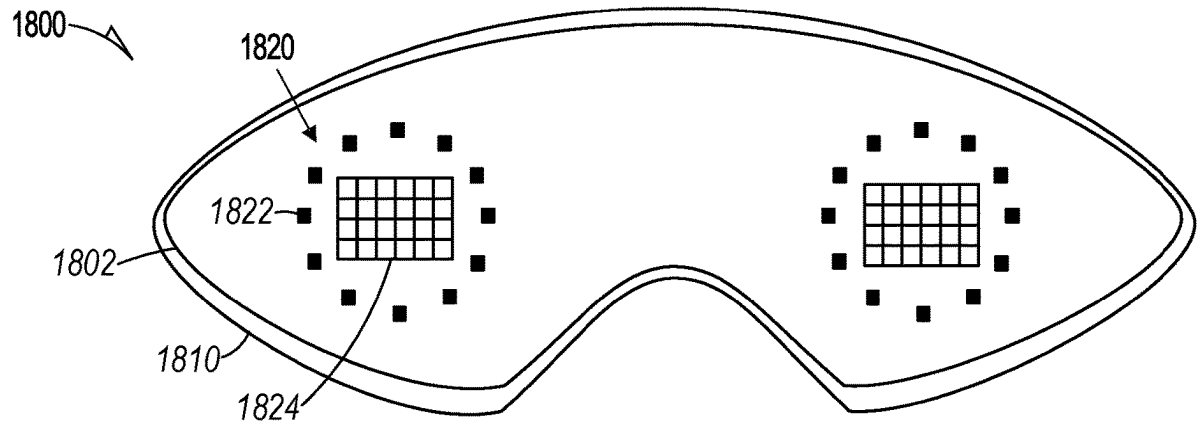
(57) **ABSTRACT**

A virtual reality (VR) headset, system, and method of fabrication are disclosed. The VR headset includes a frame, a transparent display that includes an array of light-emitting diodes (LEDs), and a darkening layer having a controllable opacity, and a processor controlling the display and darkening layer. A proximity sensor detects a potential collision, and the opacity is changed from opaque to transparent in response to detection of the potential collision. The opacity is changed in response to activation of a virtual user input or predetermined eye movement.

23 Claims, 20 Drawing Sheets



(51) **Int. Cl.**

G06F 3/01	(2006.01)
H01L 23/538	(2006.01)
H01L 25/075	(2006.01)
H05B 45/30	(2020.01)
H10H 20/01	(2025.01)
H10H 20/85	(2025.01)
H10H 20/852	(2025.01)
H10H 20/853	(2025.01)
H10H 20/856	(2025.01)
H10H 20/857	(2025.01)
H10H 29/14	(2025.01)

(52) **U.S. Cl.**

CPC *G02B 2027/0145* (2013.01); *G02B 2027/0178* (2013.01); *G02B 2027/0196* (2013.01); *H10H 20/0362* (2025.01); *H10H 20/0363* (2025.01); *H10H 20/0364* (2025.01)

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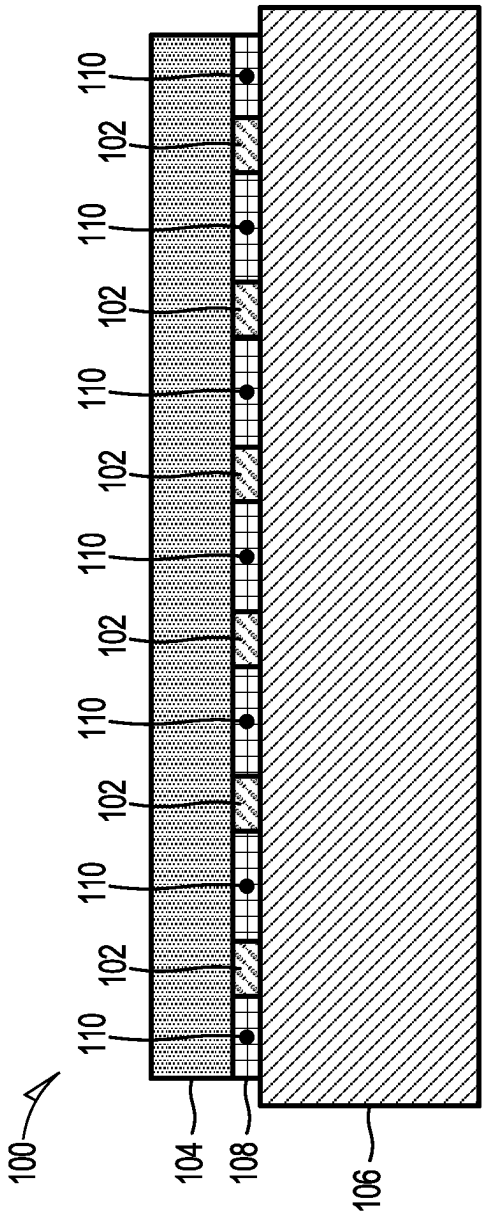
110
102
110
102
110
102
110
102
110
102
110
102
110
100
104
108
106

FIG. 1

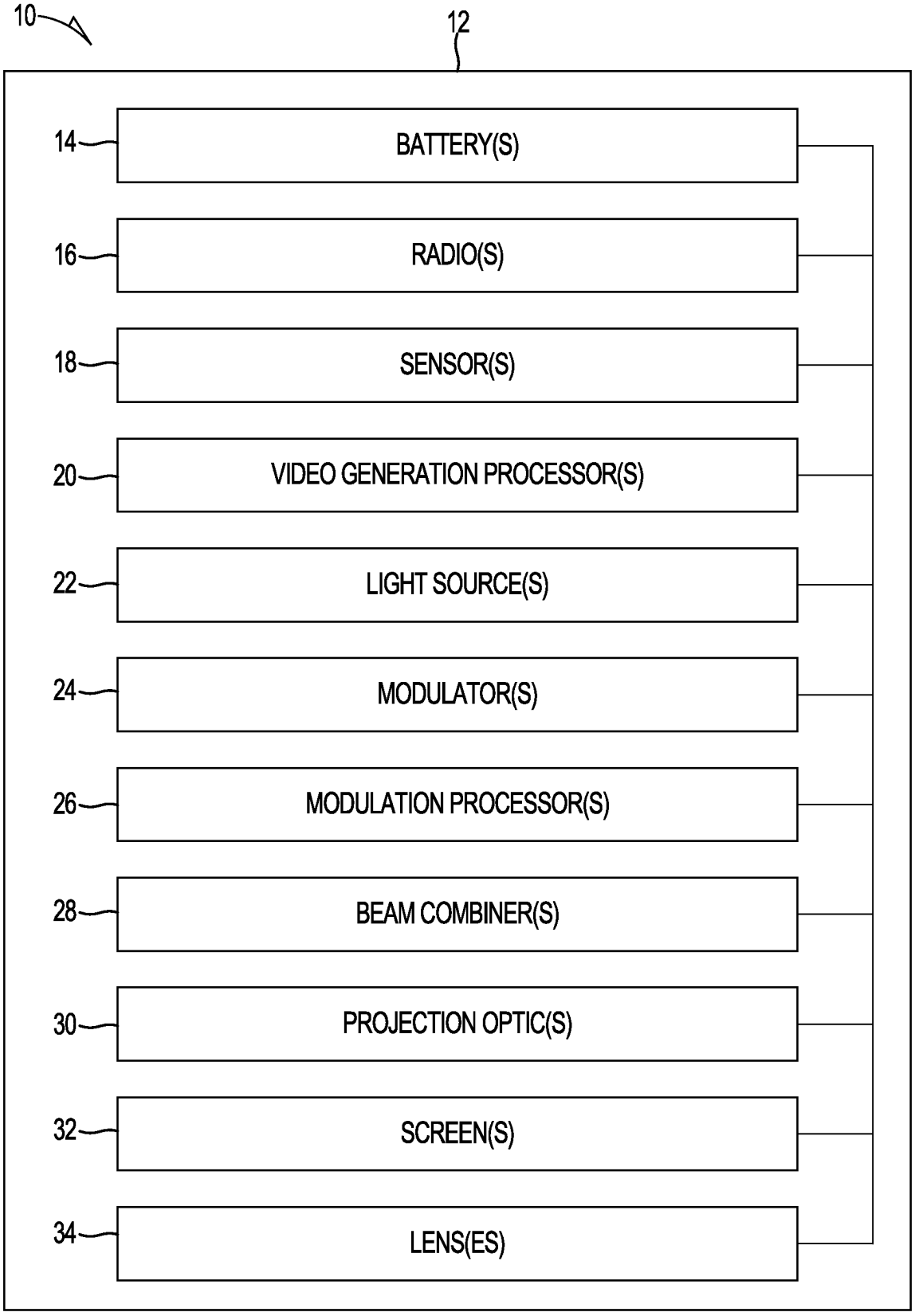
10
12
14
BATTERY(S)
16
RADIO(S)
18
SENSOR(S)
20
VIDEO GENERATION PROCESSOR(S)
22
LIGHT SOURCE(S)
24
MODULATOR(S)
26
MODULATION PROCESSOR(S)
28
BEAM COMBINER(S)
30
PROJECTION OPTIC(S)
32
SCREEN(S)
34
LENS(ES)

FIG. 2

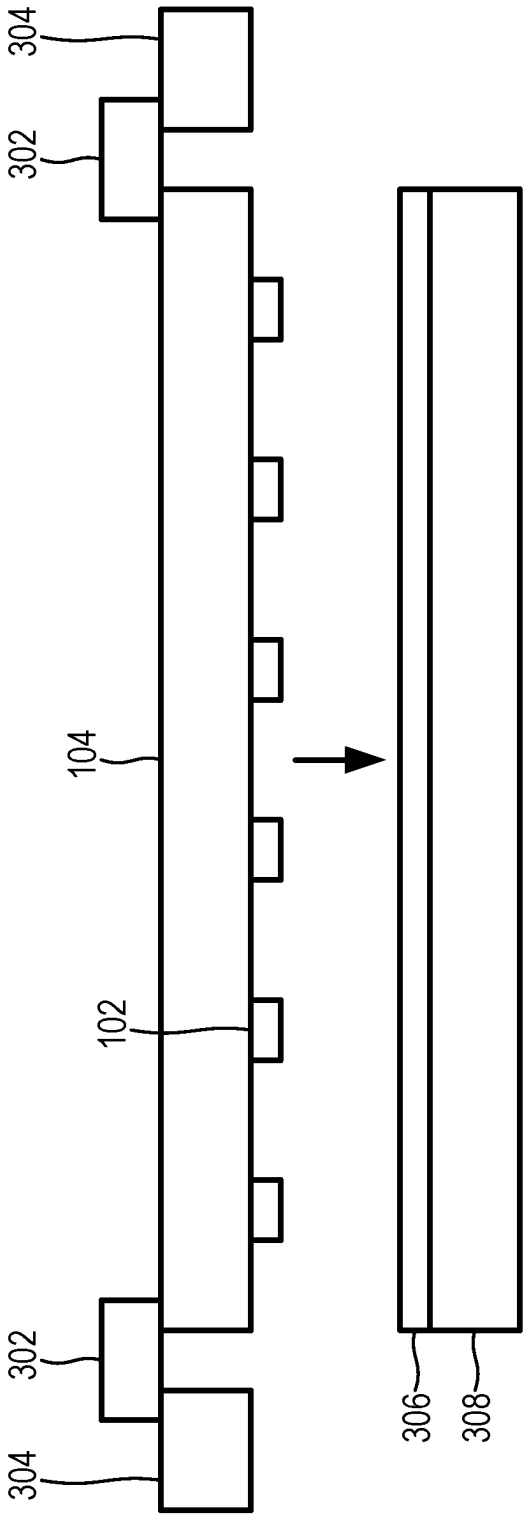

FIG. 3

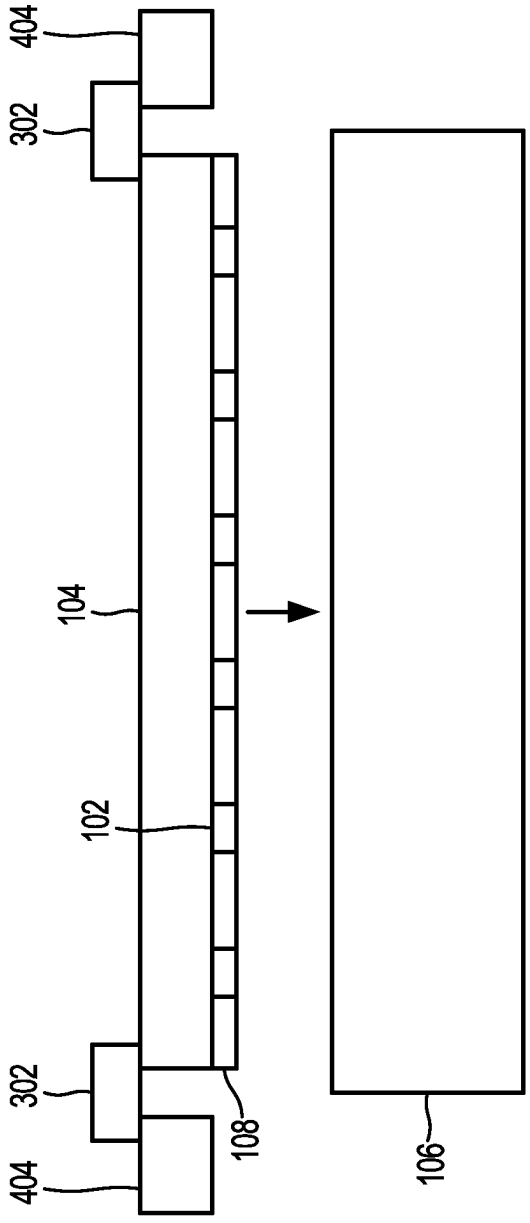

FIG. 4

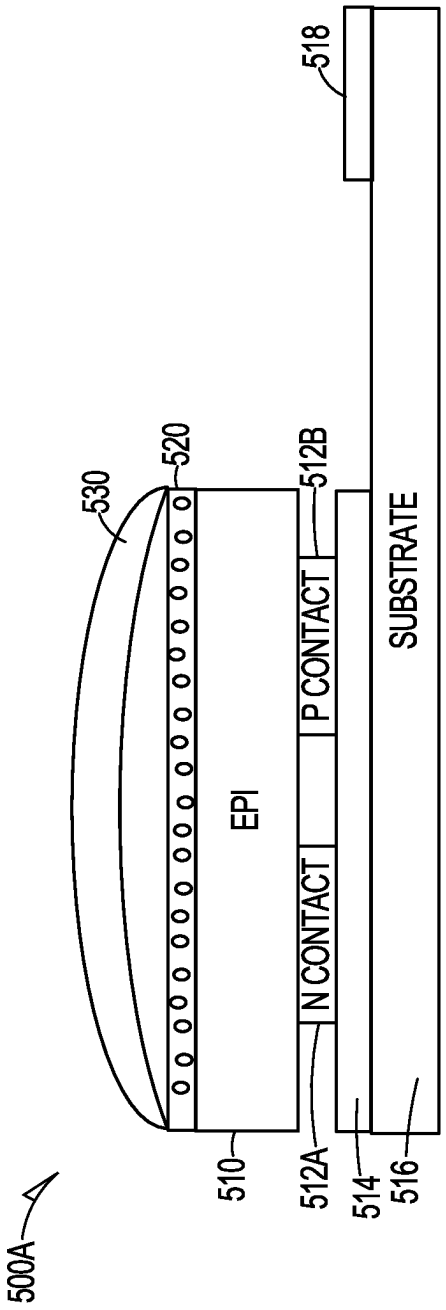
500A
510
512A
514
516
518
520
530
512B
EPI
N CONTACT
P CONTACT
SUBSTRATE

FIG. 5A

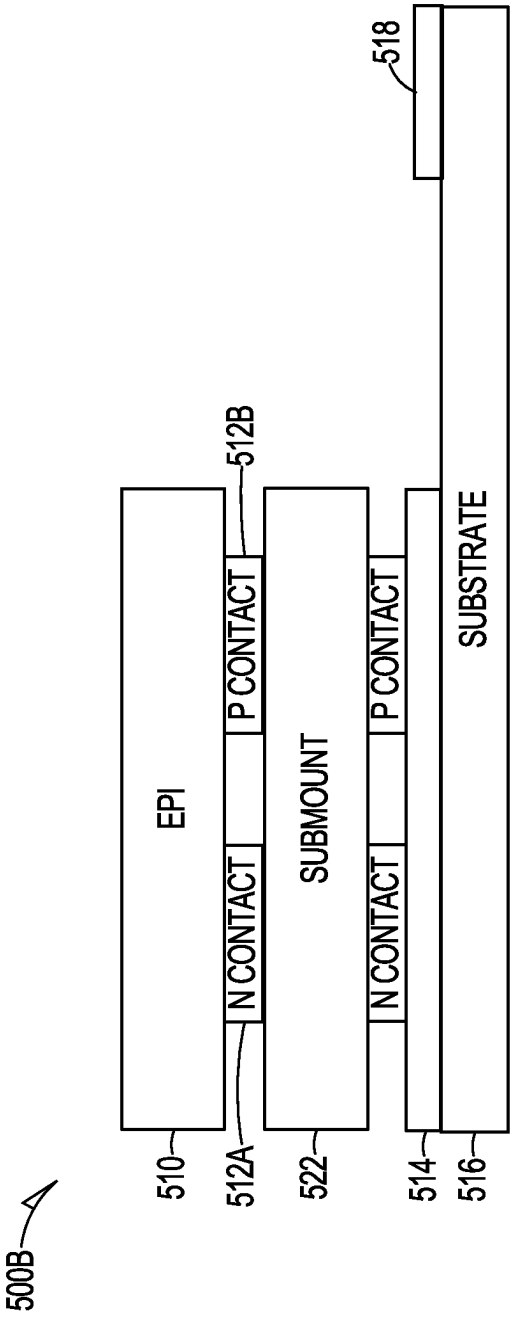
500B
510
512A
512B
N CONTACT
P CONTACT
EPI
522
SUBMOUNT
N CONTACT
P CONTACT
514
516
SUBSTRATE
518

FIG. 5B

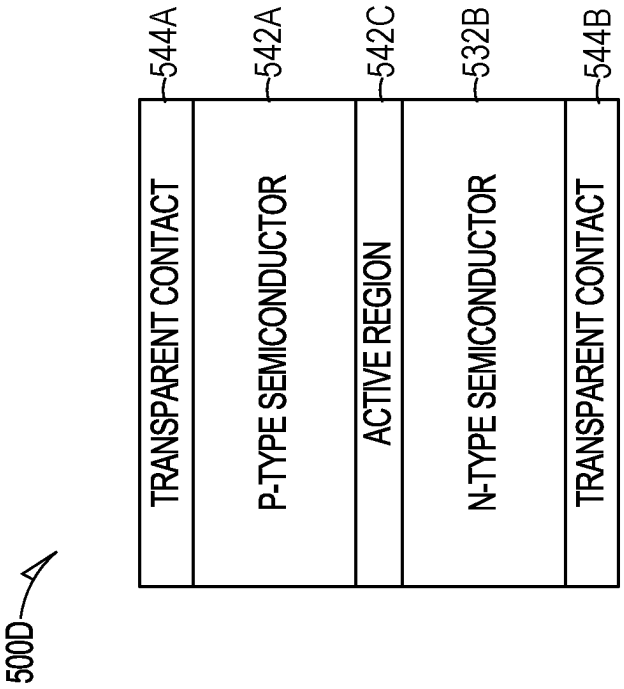
500D
544A
542A
542C
532B
544B
TRANSPARENT CONTACT
P-TYPE SEMICONDUCTOR
ACTIVE REGION
N-TYPE SEMICONDUCTOR
TRANSPARENT CONTACT

FIG. 5D

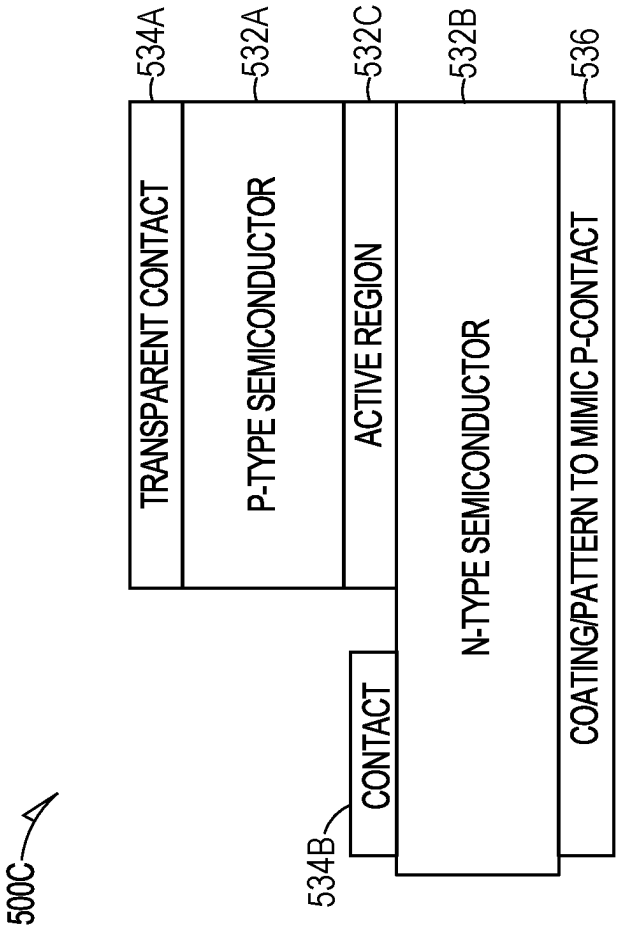
500C
534A
532A
532C
532B
536
534B
TRANSPARENT CONTACT
P-TYPE SEMICONDUCTOR
ACTIVE REGION
N-TYPE SEMICONDUCTOR
COATING/PATTERN TO MIMIC P-CONTACT
CONTACT

FIG. 5C

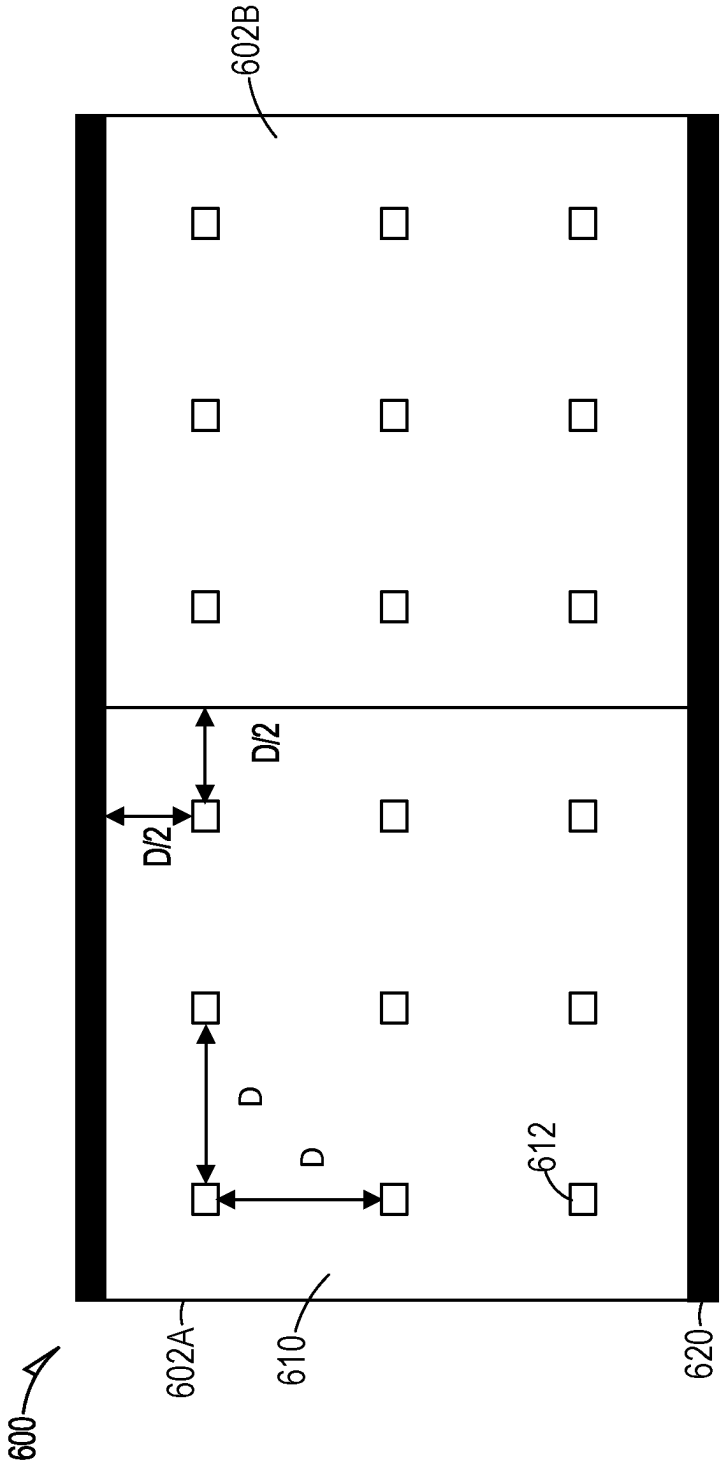

FIG. 6

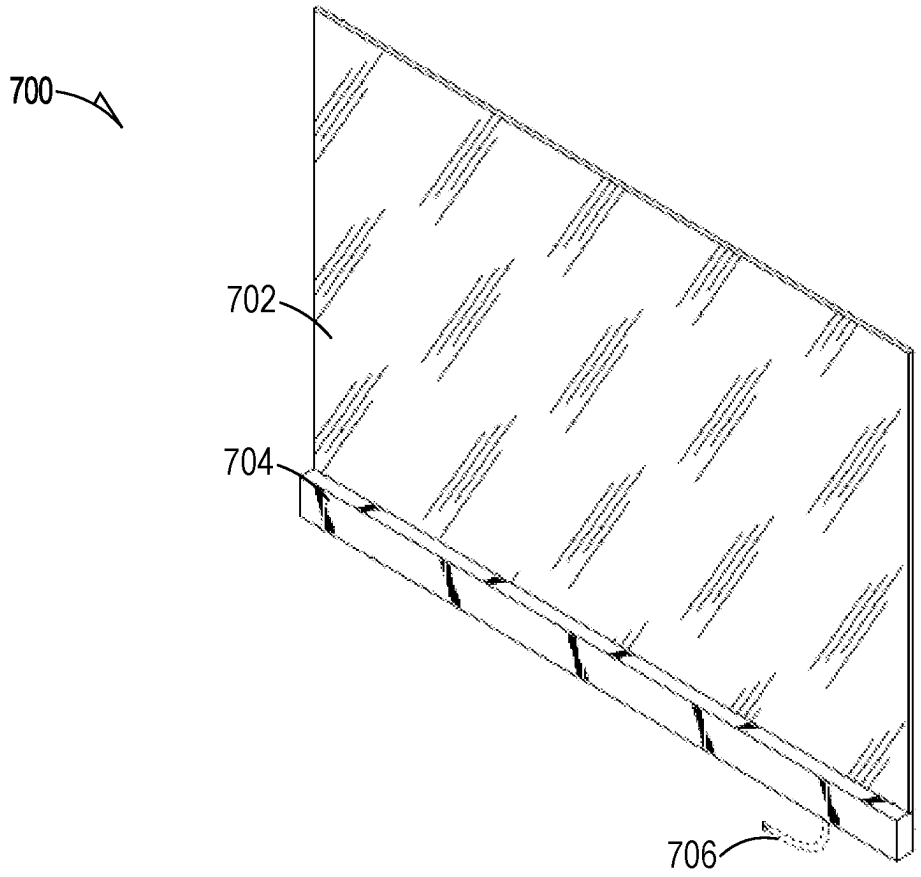

FIG. 7

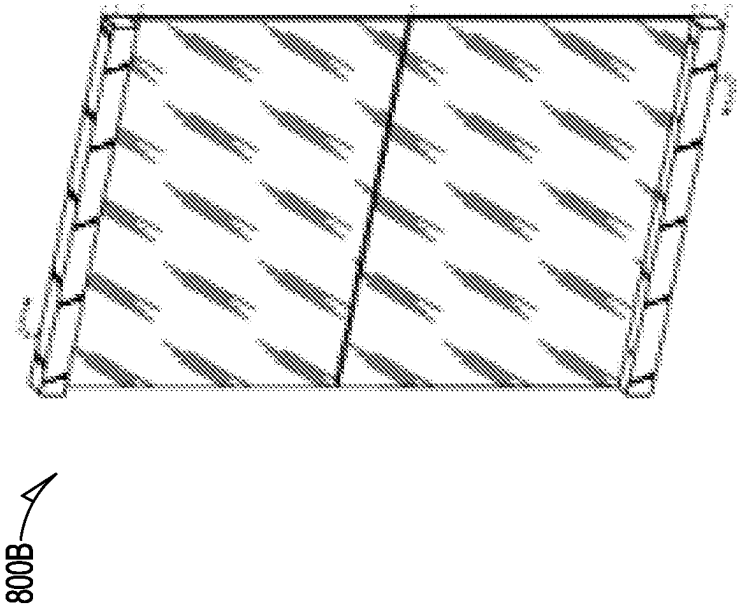

FIG. 8B

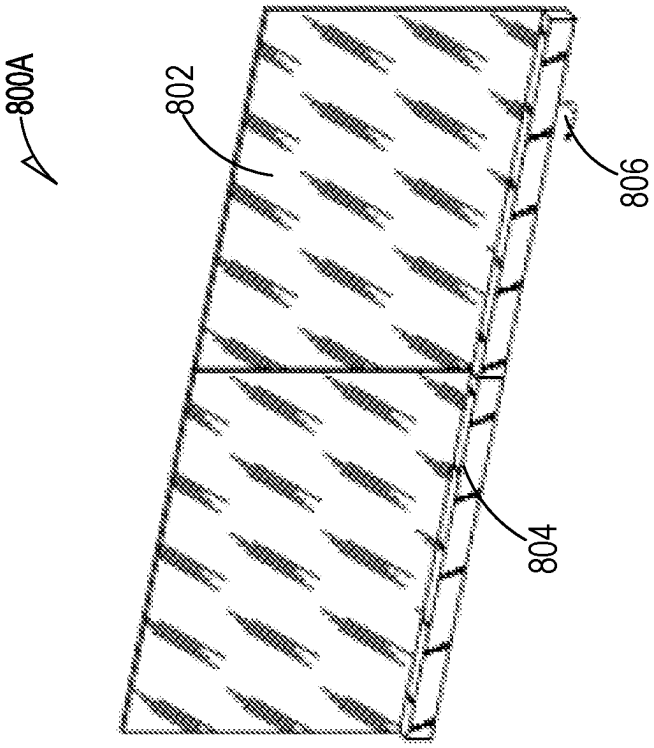

FIG. 8A

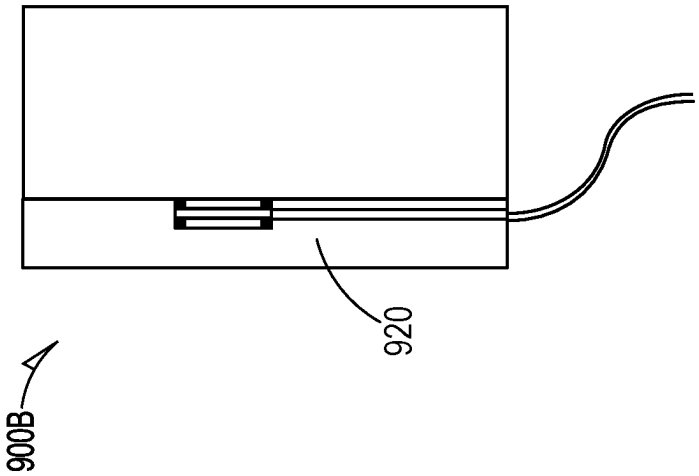

FIG. 9B

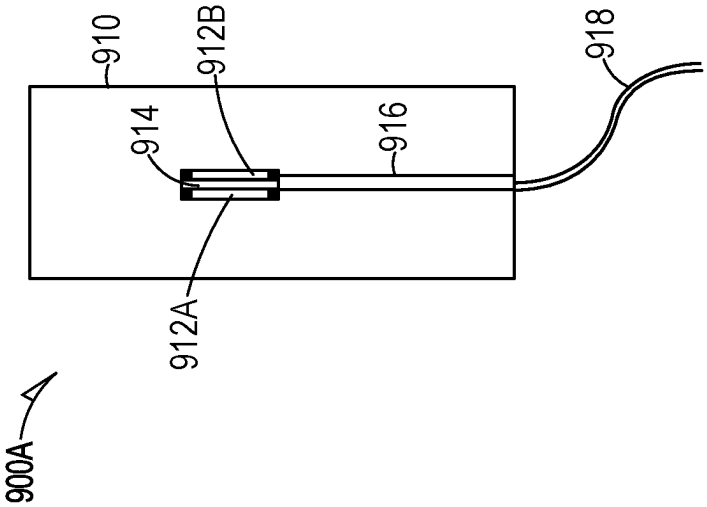

FIG. 9A

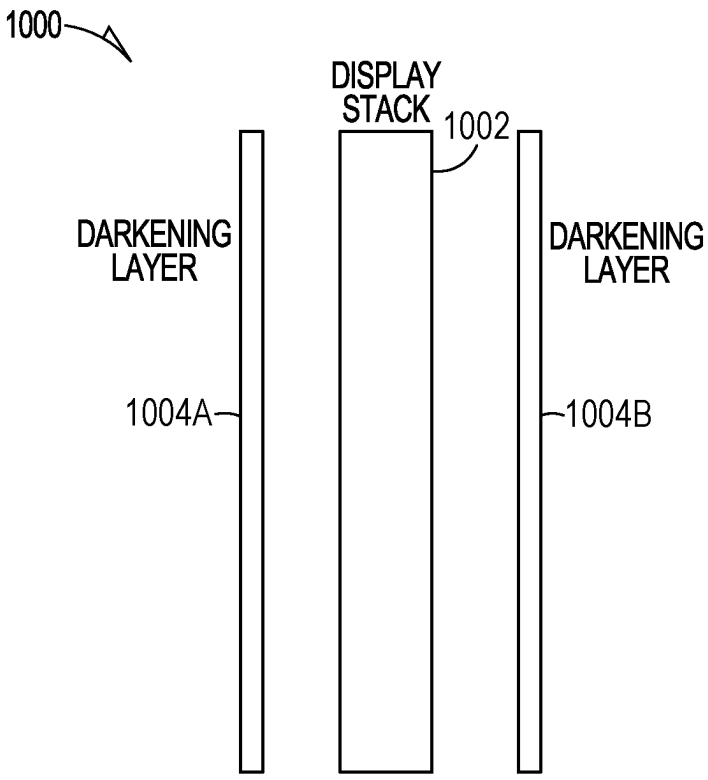
1000
DISPLAY STACK
1002
DARKENING LAYER
DARKENING LAYER
1004A
1004B

FIG. 10

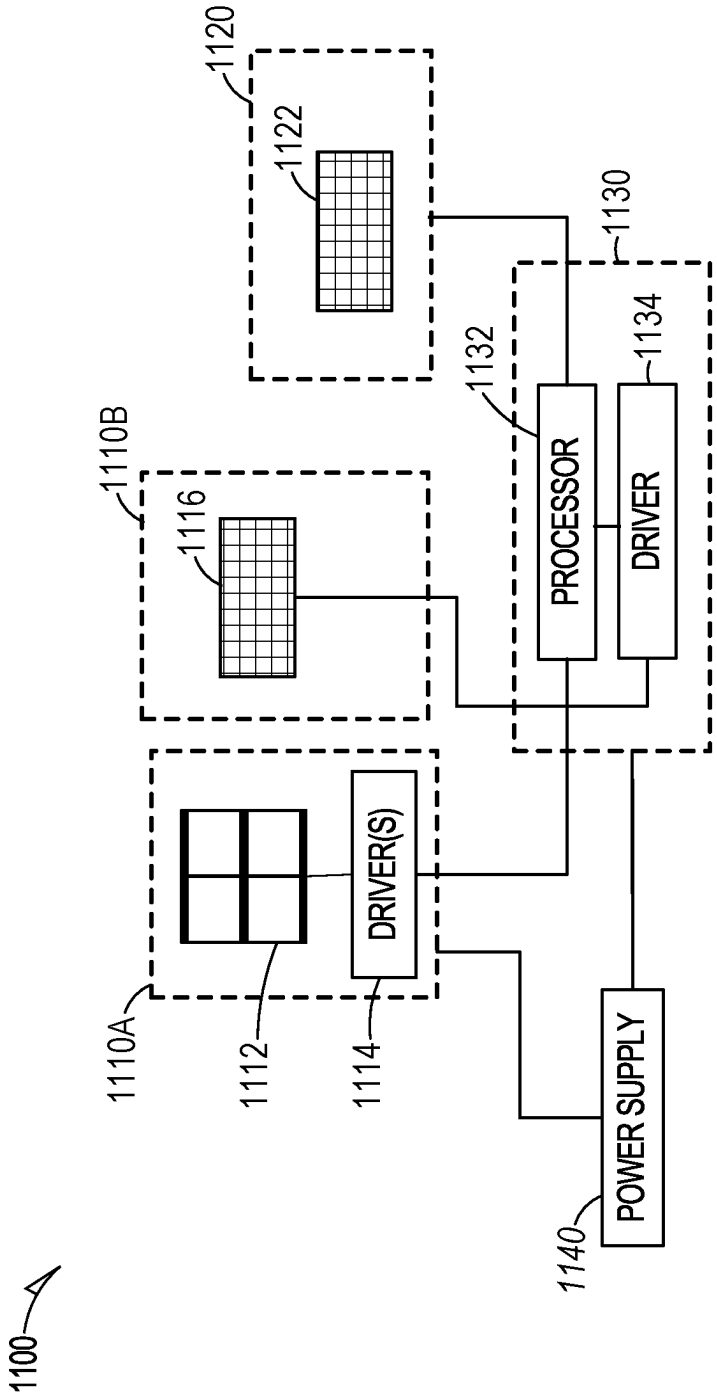
1100
1110A
1112
1114
DRIVER(S)
1110B
1116
1120
1122
1130
1132
PROCESSOR
1134
DRIVER
1140
POWER SUPPLY

FIG. 11

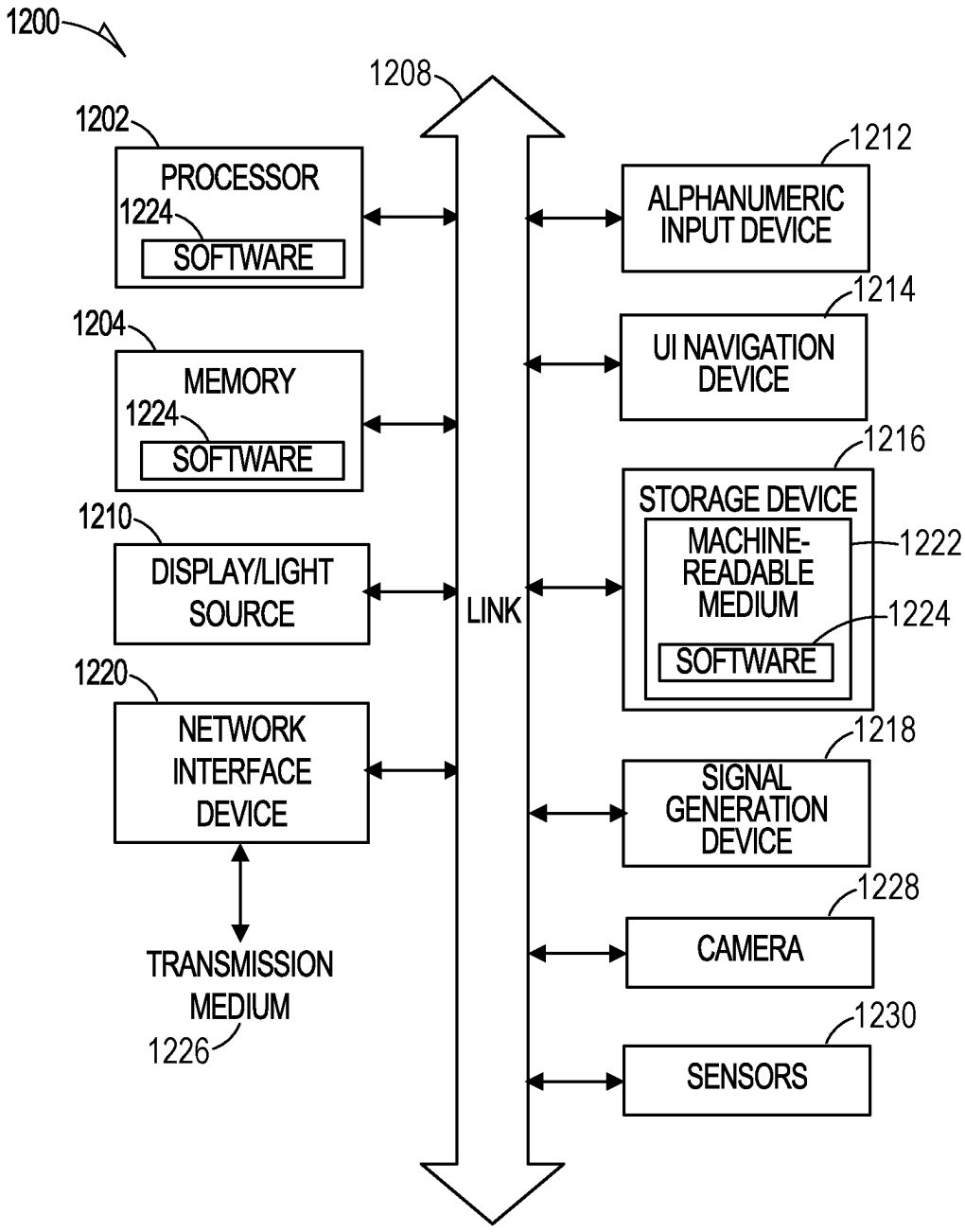
1200
1208
1202
PROCESSOR
1224
SOFTWARE
1204
MEMORY
1224
SOFTWARE
1210
DISPLAY/LIGHT SOURCE
1220
NETWORK INTERFACE DEVICE
TRANSMISSION MEDIUM
1226
LINK
1212
ALPHANUMERIC INPUT DEVICE
1214
UI NAVIGATION DEVICE
1216
STORAGE DEVICE
MACHINE-READABLE MEDIUM
1222
1224
SOFTWARE
1218
SIGNAL GENERATION DEVICE
1228
CAMERA
1230
SENSORS

FIG. 12

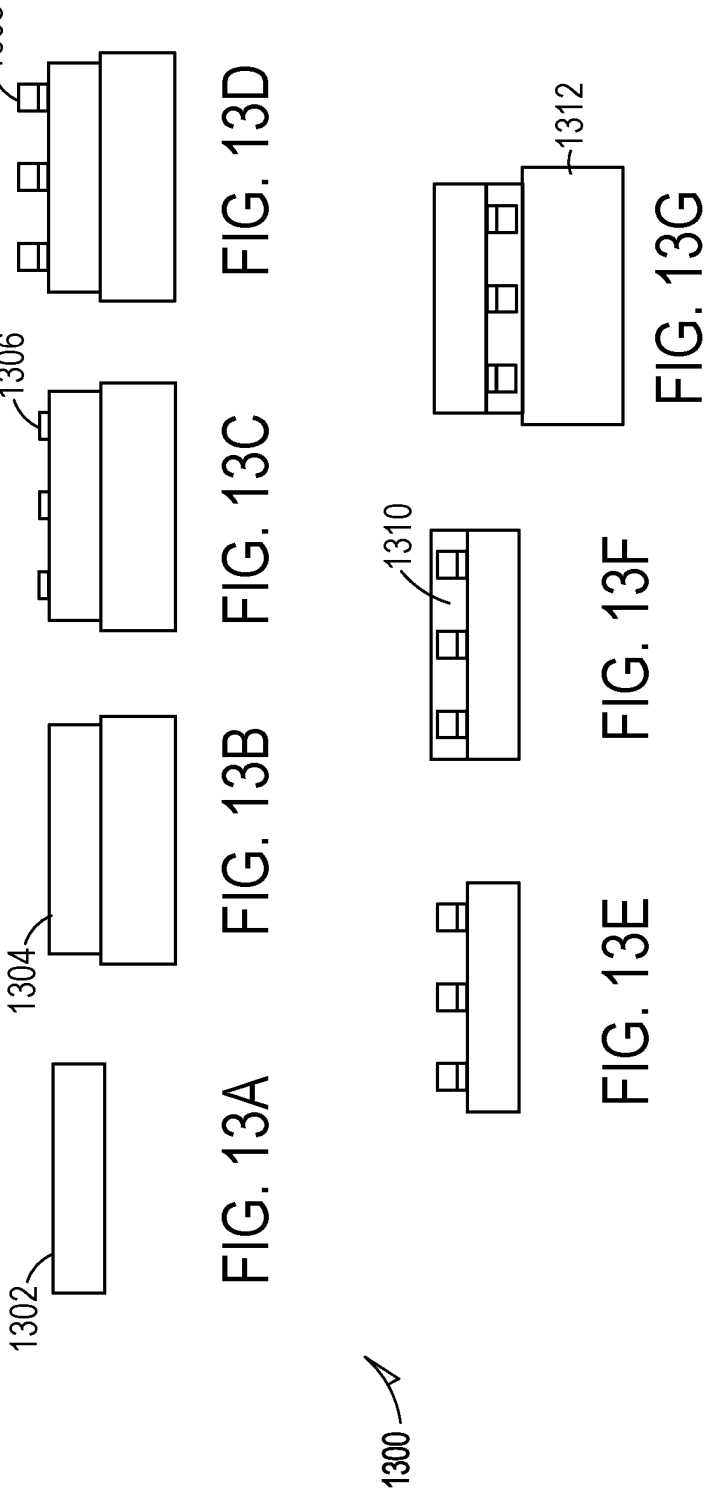

FIG. 13A FIG. 13B FIG. 13C FIG. 13D FIG. 13E FIG. 13F FIG. 13G

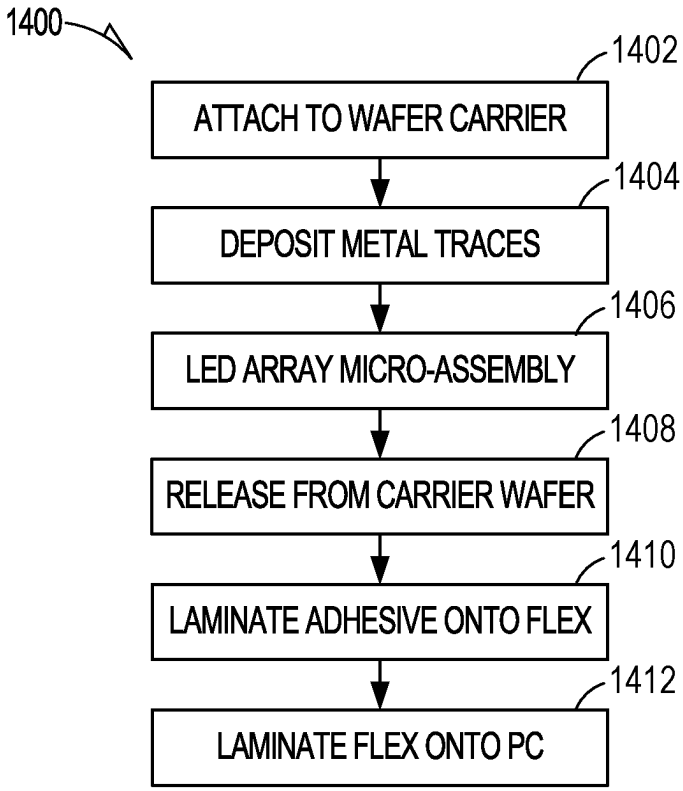
1400
1402
ATTACH TO WAFER CARRIER
1404
DEPOSIT METAL TRACES
1406
LED ARRAY MICRO-ASSEMBLY
1408
RELEASE FROM CARRIER WAFER
1410
LAMINATE ADHESIVE ONTO FLEX
1412
LAMINATE FLEX ONTO PC

FIG. 14

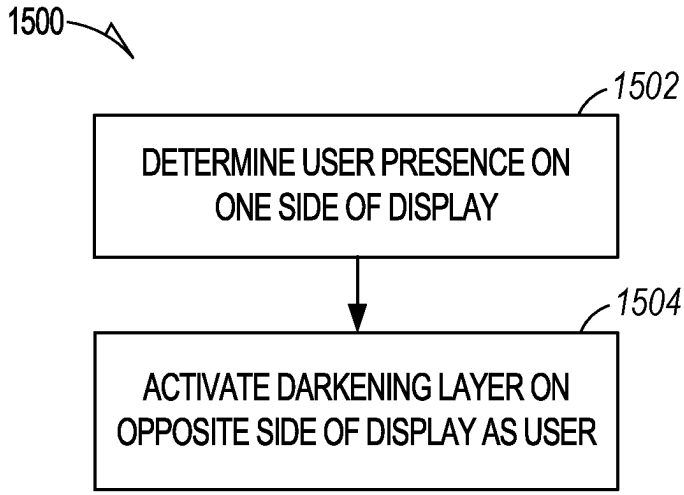
1500
1502
DETERMINE USER PRESENCE ON ONE SIDE OF DISPLAY
1504
ACTIVATE DARKENING LAYER ON OPPOSITE SIDE OF DISPLAY AS USER

FIG. 15

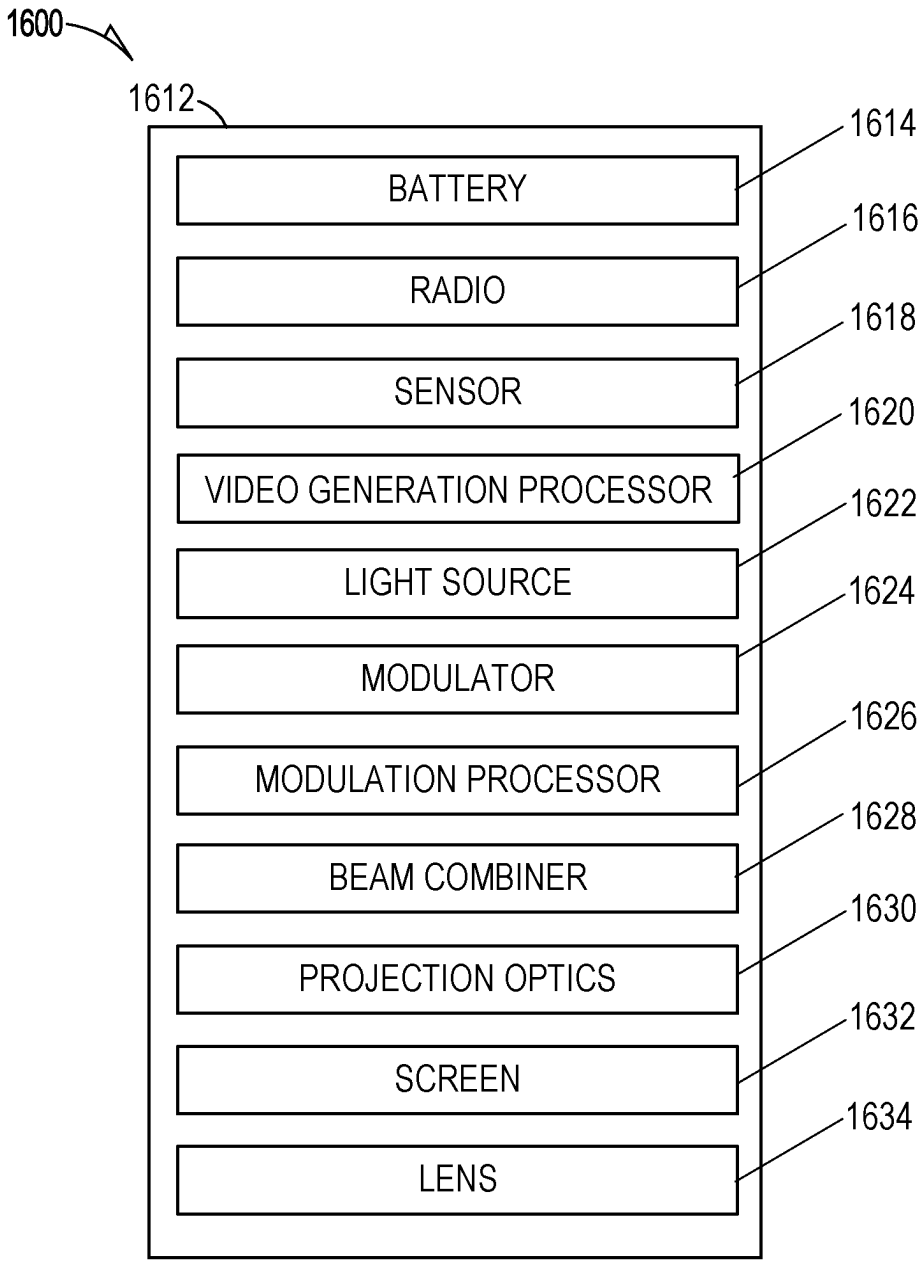
1600
1612
1614
BATTERY
1616
RADIO
1618
SENSOR
1620
VIDEO GENERATION PROCESSOR
1622
LIGHT SOURCE
1624
MODULATOR
1626
MODULATION PROCESSOR
1628
BEAM COMBINER
1630
PROJECTION OPTICS
1632
SCREEN
1634
LENS

FIG. 16

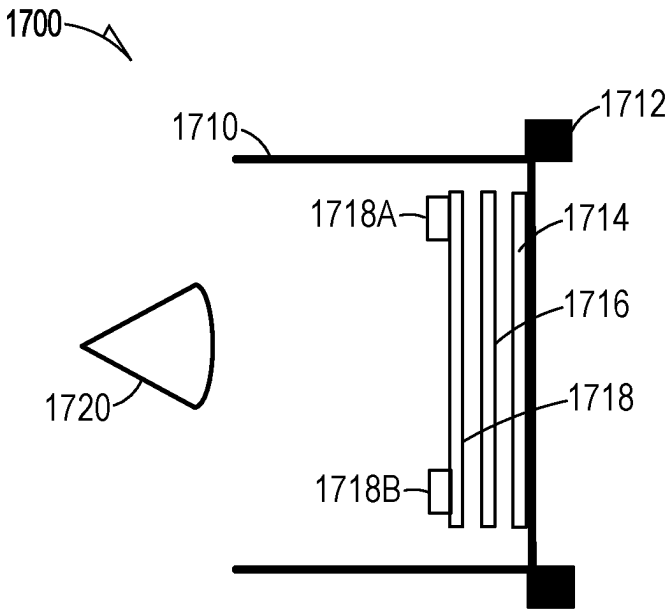

FIG. 17

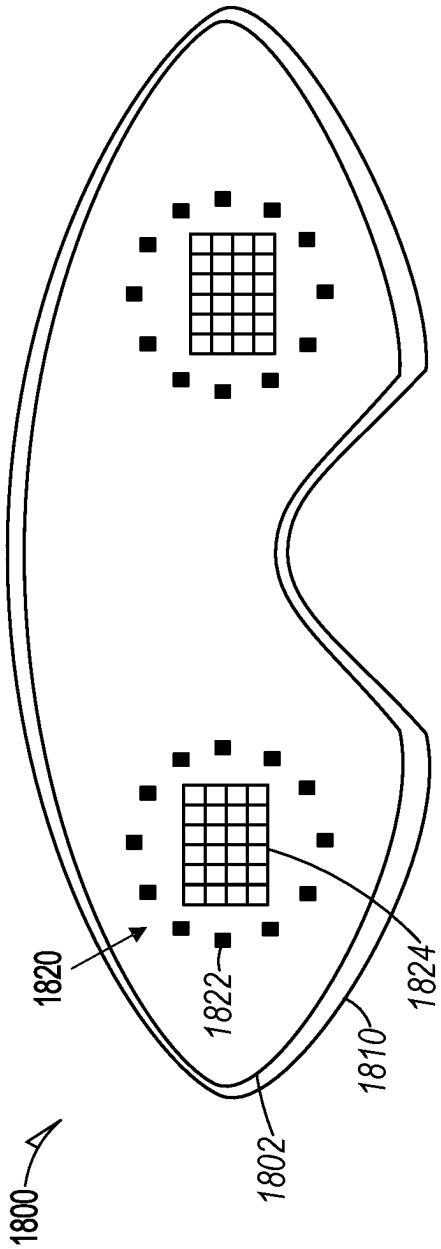

FIG. 18

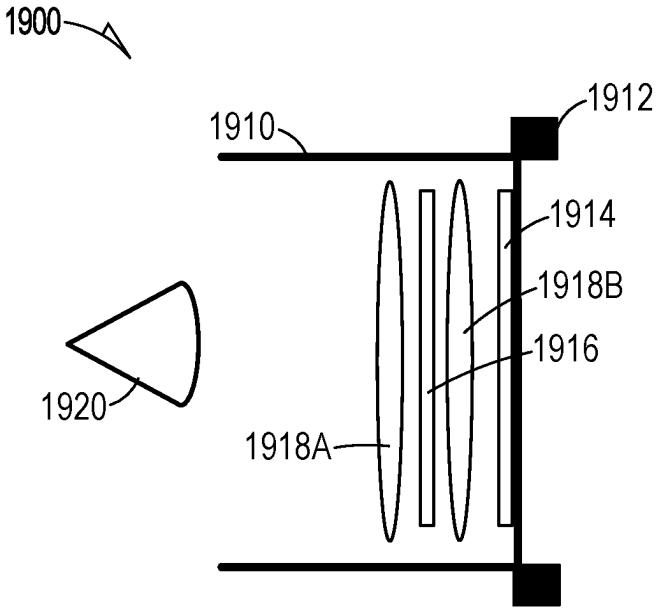
1900
1910
1912
1914
1918B
1916
1920
1918A

FIG. 19

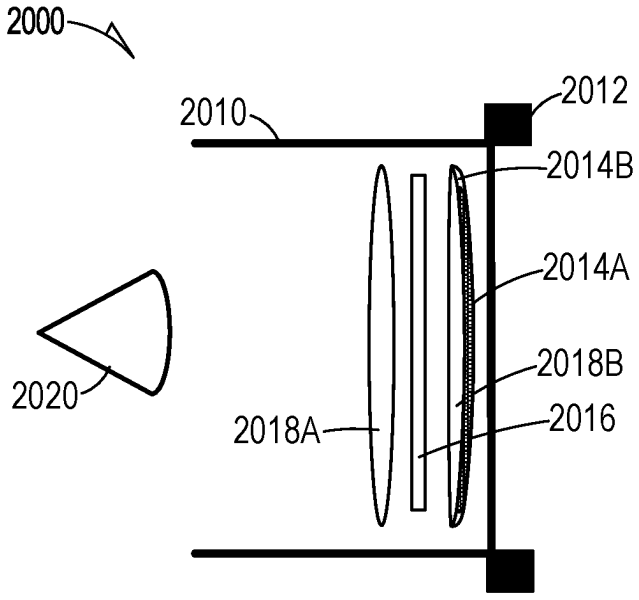
2000
2010
2012
2014B
2014A
2018B
2016
2020
2018A

FIG. 20

TRANSPARENT MICROLED DISPLAY FOR VR HEADSETS

PRIORITY

This patent application claims the benefit of priority to U.S. Provisional Patent Application Ser. No. 63/352,517, filed on Jun. 15, 2022, which is hereby incorporated by reference herein in its entirety.

FIELD OF THE DISCLOSURE

The present disclosure relates to sparse light-emitting diodes (LEDs) arrays, systems, and applications.

BACKGROUND OF THE DISCLOSURE

LEDs provide an efficient and relatively smaller source of light compared to conventional light sources. The use of LEDs has evolved from systems that provide purely lighting to more complicated systems that use light in various ways other than merely to provide illumination of an area. Consequently, there is ongoing effort to improve technology that uses LED arrays, as well as find additional uses for LED arrays.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1** shows a cross-sectional side view of an example of a light source.

FIG. **2** shows a block diagram of an example of a visualization system, which can include the light source of FIG. **1**.

FIGS. **3** and **4** show side-view drawings of the light source of FIG. **1** in various stages of assembly.

FIG. **5**A-**5**D each illustrate a cross-sectional view of an LED of a sparse array, in accordance with some examples.

FIG. **6** shows a top view of an example panel in accordance with various embodiments of the disclosed subject-matter.

FIG. **7** illustrates an example of a panel with a single tile in accordance with various embodiments of the disclosed subject-matter.

FIGS. **8**A-**8**B illustrate an example of a panel with multiple display tiles in accordance with various embodiments of the disclosed subject-matter.

FIGS. **9**A and **9**B show examples of a sparse LED array arrangement in accordance with various embodiments of the disclosed subject-matter.

FIG. **10** shows an example display in accordance with various embodiments of the disclosed subject-matter.

FIG. **11** shows an example system in accordance with various embodiments of the disclosed subject-matter.

FIG. **12** illustrates an example of a general device in accordance with some embodiments.

FIGS. **13**A-**13**G process operations of fabricating the sparse array in accordance with some embodiments.

FIG. **14** illustrates an example of a method of fabricating the sparse array in accordance with the process operations shown in FIGS. **13**A-**13**G.

FIG. **15** illustrate an example of a process of operating a VR headset in accordance with various embodiments of the disclosed subject-matter.

FIG. **16** shows a block diagram of an example of a system in accordance with various embodiments of the disclosed subject-matter.

FIG. **17** illustrates an example VR headset in accordance with various embodiments of the disclosed subject-matter.

FIG. **18** illustrates another example VR headset in accordance with various embodiments of the disclosed subject-matter.

FIG. **19** illustrates an example VR headset in accordance with various embodiments of the disclosed subject-matter.

FIG. **20** illustrates an example VR headset in accordance with various embodiments of the disclosed subject-matter.

Corresponding reference characters indicate corresponding parts throughout the several views. Elements in the drawings are not necessarily drawn to scale. The configurations shown in the drawings are merely examples and should not be construed as limiting in any manner.

DETAILED DESCRIPTION

The use of the transparent displays, described herein, which are enabled by microLEDs, may be able to expand capability in user experience by providing signage, interactive menus, entrance criteria, public information, and many other cases. The user experience may be enhanced, for example, by allowing for rich augmented reality (AR) and/or virtual reality (VR) experiences, entertainment, and many other cases.

For the purposes of this document, the term "micro-LED" is intended to be synonymous with an LED of a sparse array of LEDs as defined herein. There is ongoing effort to improve micro-LED display technology. For example, displays, such as direct-view displays and projection displays, can use micro-LEDs to improve efficiency and increase brightness. Note that the terms "substantially transparent" and "transparent" are used interchangeably herein to refer to materials (such as metal oxides or very thin metals) through which light from the microLEDs passes without being substantially (more than a few percent) absorbed or reflected.

In a direct-view micro-LED display, the LEDs may occupy a relatively small fraction of the display area. Because most of the display area is unaffected by the LEDs, the LEDs may not substantially alter the optical properties of the surface on which they are assembled. For example, a black surface may remain black in the presence of LEDs mounted on the black surface. Similarly, a reflective surface may remain reflective in the presence of LEDs mounted on the reflective surface. Other examples and optical surface properties can also be used.

In some examples, the micro-LEDs can be assembled onto a transparent flexible substrate. The transparent flexible substrate can then be laminated onto a substrate that has desired optical properties, such as being reflective, and so forth. Using the transparent flexible substrate in this manner can allow micro-LEDs to be applied to a curved or irregularly shaped substrate, which may not be compatible with micro-LED assembly technologies that use a rigid, flat substrate, such as a wafer.

In some examples, the flexible substrate can be laminated LED-side down onto the substrate, using a transparent adhesive that has sufficient thickness to encapsulate the micro-LEDs. For these examples and others, the transparent substrate and adhesive can also function as a barrier that can protect the micro-LEDs from the environment. Because the transparent substrate can provide protection for the micro-LEDs, the transparent substrate can reduce or eliminate the need to use an additional transparent cover or protection layer to provide the protection for the micro-LEDs.

FIG. **1** shows a cross-sectional side view of an example of a light source **100**. The light source **100** can include a sparse array of LEDs **102** (e.g., "micro-LEDs") disposed on a transparent flexible substrate **104**, and a rigid substrate **106** adhered to the transparent flexible substrate **104** with an adhesive layer **108** such that the sparse array of LEDs **102** is located between the rigid substrate **106** and the transparent flexible substrate **104**. The sparse array of LEDs **102** can be encapsulated in the adhesive **110** of the adhesive layer **108**.

The transparent flexible substrate **104** can be a polymer sheet with a relatively high transmittance, or, equivalently, relatively low losses due to absorption and scattering in the visible portion of the electromagnetic spectrum, such as between wavelengths of about 400 nm and about 700 nm. Suitable materials for the transparent flexible substrate **104** can include clear polyimide (PI), polyethylene naphthalate (PEN), polyethylene terephthalate (PET) and others. The transparent flexible substrate **104** can have a thickness between about 20 μm and about 200 μm, although a thickness outside this range of thicknesses can also be used.

The sparse array of LEDs **102** can be disposed on the transparent flexible substrate **104**. For the purposes of this document, the term sparse is intended to signify that a light-producing surface area of the array is less, or significantly less, than a total surface area of the array. For example, a fill factor of the array (e.g., a ratio of light-producing surface area to full surface area) can be less than or equal to a specified threshold, such as 10%, 5%, 4%, 3%, 2%, 1%, or another suitable threshold. As a specific example, the LEDs **102** can be arranged in a rectangular array, with center-to-center spacing along one dimension denoted by spacing x. Each LED **102** can have a light-producing area sized along the one dimension by size s. The ratio of s divided by x can be less than or equal to 0.1. In an orthogonal dimension, a similar ratio applies, with the linear size of a light-producing area being less than or equal to one-tenth the linear center-to-center spacing of the LEDs **102**. Combining the two linear dimensions, the surface area of the light-producing areas of the LEDs **102** is less than or equal to 1% of the surface area of the array. In some examples, the light-producing area of each LED can be smaller than 200 μm on a side. In some examples, the light-producing area of each LED can be smaller than 50 μm on a side. Electrical traces can be deposited on the transparent flexible substrate **104** to electrically power (e.g., carry current to and from) the LEDs **102**. In some examples, the electrical traces can be metal traces that are narrow enough to be invisible under typical viewing conditions. In some examples the electrical traces can be formed from one or more transparent electrically conductive materials, such as indium tin oxide (ITO). Each of these examples of electrical traces (e.g., narrow metal traces and transparent electrically conductive materials) may be considered to provide transparent electrical traces.

In some examples, the sparse array of LEDs **102** can include two or more LEDs **102** that emit light at a same wavelength (or color). In some examples, the sparse array of LEDs **102** can include LEDs **102** that all emit light at a same wavelength. For example, a device, such as a display, can include a sparse array of LEDs **102** that all emit red light, a sparse array of LEDs **102** that all emit green light, and a sparse array of LEDs **102** that all emit blue light. In some examples, the sparse array of LEDs **102** can include two or more LEDs **102** that emit light at different wavelengths. For example, a device, such as a display, can include a sparse array of LEDs **102** in which some LEDs **102** emit red light, some LEDs **102** emit green light, and some LEDs **102** can emit blue light. The red, green, and blue LEDs **102** can be arranged in repeating clusters, with each cluster forming a color pixel of the device. In some examples, the sparse array of LEDs **102** can include at least one LED that emits light at a visible wavelength (e.g., between about 400 nm and about 700 nm). In some examples, the sparse array of LEDs **102** can include at least one LED that emits light at an infrared wavelength (e.g., greater than about 700 nm). Such infrared wavelengths can be used for biometric sensing or other sensing techniques.

Because the sparse array of LEDs **102**, including the light-emitting area of the LEDs **102**, the corresponding electrical traces, and any corresponding circuitry, can have a relatively small fill factor, most of the surface area of the sparse array of LEDs **102** can be transparent. For example, light incident on the sparse array of LEDs **102**, either incident from the transparent flexible substrate **104** or incident on the transparent flexible substrate **104**, mostly passes through the sparse array of LEDs **102**, with only a relatively small fraction being blocked by the light-emitting areas and electrical traces of the sparse array of LEDs **102**.

As a result, the sparse array of LEDs **102** can produce light on a surface and/or an optical element that has an additional function, such as on the rigid substrate **106**, described below. For example, the surface and/or optical element can include a reflector that has a specified value of reflectance. As another example, the surface and/or optical element can include a spectral filter that has a specified reflectance, transmittance, or absorptance at one or more specified wavelengths. Other suitable functions can also be used.

The rigid substrate **106** can be adhered to the transparent flexible substrate **104**. In some examples, the rigid substrate **106** can be transparent. Suitable applications for a transparent rigid substrate **106** can include a building window, a heads-up display, an augmented reality headset, and others. Suitable transparent materials for a transparent rigid substrate **106** can include glass, laminated glass, polycarbonate, or an engineering plastic such as poly(methyl methacrylate) (PMMA).

In some examples, the rigid substrate **106** can be reflective. In some examples, the rigid surface can be specularly reflective (e.g., can have a relatively smooth reflective surface that causes relatively little scattering or diffusion upon reflection). Suitable applications for a reflective rigid substrate **106** can include a mirror, such as a vehicular rear-view mirror or side-view mirror that can display information. Specifically, the specularly reflective surface of the rigid substrate **106** can perform the function of reflecting light from the rear of a vehicle, while the sparse array of LEDs **102** can display information superimposed on the reflected light.

In some examples, the rigid substrate **106** can be protective and/or decorative, such as a case material of a mobile device, such as a smart phone. The rigid substrate **106** can include other suitable optical properties and perform other suitable functions as well.

The rigid substrate **106** can be flat (e.g., substantially flat) or curved. Curved substrates can be used in vehicle windshields, augmented reality headsets, wearables, or other suitable devices. In some examples, the rigid substrate **106** is formed as a single unitary body. In other examples, the rigid substrate **106** can include multiple rigid substrate elements. For example, multiple rigid substrate elements can be used to create a folding display in a smartphone or other mobile device. Custom tooling can support such curved substrates in the lamination process, described below.

The adhesive can adhere the rigid substrate **106** to the transparent flexible substrate **104**. In some examples, the adhesive can be formed as an adhesive layer **108** such that the sparse array of LEDs **102** is located between the rigid substrate **106** and the transparent flexible substrate **104**. Other suitable configurations can also be used. Suitable materials for the adhesive of the adhesive layer **108** can include silicone, epoxy silicone, an acrylic film, an epoxy film, and others.

In some examples, the adhesive of the adhesive layer **108** can be formed from a material having a refractive index that can match or substantially match a refractive index of the transparent flexible substrate **104** and/or the rigid substrate **106** or can fall between refractive indices of the transparent flexible substrate **104** and the rigid substrate **106**. Selecting a refractive index in this manner can reduce or eliminate reflections at the interface between the adhesive layer **108** and the transparent flexible substrate **104** and/or at the interface between the adhesive layer **108** and the rigid substrate **106**. For example, the adhesive of the adhesive layer **108** can be formed from a material having a refractive index between about 1.4 and about 1.7. Using a refractive index in the range of about 1.4 to about 1.7 can reduce unwanted reflections between the adhesive layer **108** and the transparent flexible substrate **104** and unwanted reflections between the adhesive layer **108** and the rigid substrate **106**. Optional thin-film anti-reflection coatings can also be used to help reduce or eliminate unwanted reflections at one or more interfaces between adjacent differing materials or between a material and air.

In some examples, the adhesive layer **108** can fully encapsulate the sparse array of LEDs **102**. By fully encapsulating the sparse array of LEDs **102**, the adhesive layer **108** can protect the sparse array of LEDs **102** from the environment and can form a smooth, unbroken interface with the rigid substrate **106**. To fully encapsulate the sparse array of LEDs **102**, the adhesive of the adhesive layer **108** can have a resin viscosity that is low enough such that the adhesive flows around the LEDs **102** as the adhesive is deposited. In addition, to fully encapsulate the sparse array of LEDs **102**, the adhesive layer **108** can be thick enough to fully cover the topography of the sparse array of LEDs **102**.

FIG. **2** shows a block diagram of an example of a visualization system **10**, which can include the light source **100** of FIG. **1**. The visualization system **10** can include a wearable housing **12**, such as a headset or goggles. The housing **12** can mechanically support and house the elements detailed below. In some examples, one or more of the elements detailed below can be included in one or more additional housings that can be separate from the wearable housing **12** and couplable to the wearable housing **12** wirelessly and/or via a wired connection. For example, a separate housing can reduce the weight of wearable goggles, such as by including batteries, radios, and other elements. The housing **12** can include one or more batteries **14**, which can electrically power any or all of the elements detailed below. The housing **12** can include circuitry that can electrically couple to an external power supply, such as a wall outlet, to recharge the batteries **14**. The housing **12** can include one or more radios **16** to communicate wirelessly with a server or network via a suitable protocol, such as WiFi.

The visualization system **10** can include one or more sensors **18**, such as optical sensors, audio sensors, tactile sensors, thermal sensors, gyroscopic sensors, time-of-flight sensors, triangulation-based sensors, and others. In some examples, one or more of the sensors can sense a location, a position, and/or an orientation of a user. In some examples, one or more of the sensors **18** can produce a sensor signal in response to the sensed location, position, and/or orientation. The sensor signal can include sensor data that corresponds to a sensed location, position, and/or orientation. For example, the sensor data can include a depth map of the surroundings. In some examples, such as for an augmented reality system, one or more of the sensors **18** can capture a real-time video image of the surroundings proximate a user.

The visualization system **10** can include one or more video generation processors **20**. The one or more video generation processors **20** can receive, from a server and/or a storage medium, scene data that represents a three-dimensional scene, such as a set of position coordinates for objects in the scene or a depth map of the scene. The one or more video generation processors **20** can receive one or more sensor signals from the one or more sensors **18**. In response to the scene data, which represents the surroundings, and at least one sensor signal, which represents the location and/or orientation of the user with respect to the surroundings, the one or more video generation processors **20** can generate at least one video signal that corresponds to a view of the scene. In some examples, the one or more video generation processors **20** can generate two video signals, one for each eye of the user, that represent a view of the scene from a point of view of the left eye and the right eye of the user, respectively. In some examples, the one or more video generation processors **20** can generate more than two video signals and combine the video signals to provide one video signal for both eyes, two video signals for the two eyes, or other combinations.

The visualization system **10** can include one or more light sources **22** (such as the light source **100** of FIG. **1**) that can provide light for a display of the visualization system **10**. Suitable light sources **22** can include a light-emitting diode, a monolithic light-emitting diode, a plurality of light-emitting diodes, an array of light-emitting diodes, an array of light-emitting diodes disposed on a common substrate, a segmented light-emitting diode that is disposed on a single substrate and has light-emitting diode elements that are individually addressable and controllable (and/or controllable in groups and/or subsets), an array of micro-light-emitting diodes (microLEDs), and others. In some examples, one or more of the light sources **22** can include a sparse array of LEDs disposed on a transparent flexible substrate, and a rigid substrate adhered to the transparent flexible substrate with an adhesive layer such that the sparse array of LEDs is located between the rigid substrate and the transparent flexible substrate.

A light-emitting diode can be white-light light-emitting diode. For example, a white-light light-emitting diode can emit excitation light, such as blue light or violet light. The white-light light-emitting diode can include one or more phosphors that can absorb some or all of the excitation light and can, in response, emit phosphor light, such as yellow light, that has a wavelength greater than a wavelength of the excitation light.

The one or more light sources **22** can include light-producing elements having different colors or wavelengths. For example, a light source can include a red light-emitting diode that can emit red light, a green light-emitting diode that can emit green light, and a blue light-emitting diode that can emit blue right. The red, green, and blue light combine in specified ratios to produce any suitable color that is visually perceptible in a visible portion of the electromagnetic spectrum.

The visualization system **10** can include one or more modulators **24**. The modulators **24** can be implemented in one of at least two configurations.

In a first configuration, the modulators **24** can include circuitry that can modulate the light sources **22** directly. For example, the light sources **22** can include an array of light-emitting diodes, and the modulators **24** can directly modulate the electrical power, electrical voltage, and/or electrical current directed to each light-emitting diode in the array to form modulated light. The modulation can be performed in an analog manner and/or a digital manner. In some examples, the light sources **22** can include an array of red light-emitting diodes, an array of green light-emitting diodes, and an array of blue light-emitting diodes, and the modulators **24** can directly modulate the red light-emitting diodes, the green light-emitting diodes, and the blue light-emitting diodes to form the modulated light to produce a specified image.

In a second configuration, the modulators **24** can include a modulation panel, such as a liquid crystal panel. The light sources **22** can produce uniform illumination, or nearly uniform illumination, to illuminate the modulation panel. The modulation panel can include pixels. Each pixel can selectively attenuate a respective portion of the modulation panel area in response to an electrical modulation signal to form the modulated light. In some examples, the modulators **24** can include multiple modulation panels that can modulate different colors of light. For example, the modulators **24** can include a red modulation panel that can attenuate red light from a red light source such as a red light-emitting diode, a green modulation panel that can attenuate green light from a green light source such as a green light-emitting diode, and a blue modulation panel that can attenuate blue light from a blue light source such as a blue light-emitting diode.

In some examples of the second configuration, the modulators **24** can receive uniform white light or nearly uniform white light from a white light source, such as a white-light light-emitting diode. The modulation panel can include wavelength-selective filters on each pixel of the modulation panel. The panel pixels can be arranged in groups (such as groups of three or four), where each group can form a pixel of a color image. For example, each group can include a panel pixel with a red color filter, a panel pixel with a green color filter, and a panel pixel with a blue color filter. Other suitable configurations can also be used.

The visualization system **10** can include one or more modulation processors **26**, which can receive a video signal, such as from the one or more video generation processors **20**, and, in response, can produce an electrical modulation signal. For configurations in which the modulators **24** directly modulate the light sources **22**, the electrical modulation signal can drive the light sources **24**. For configurations in which the modulators **24** include a modulation panel, the electrical modulation signal can drive the modulation panel.

The visualization system **10** can include one or more beam combiners **28** (also known as beam splitters **28**), which can combine light beams of different colors to form a single multi-color beam. For configurations in which the light sources **22** can include multiple light-emitting diodes of different colors, the visualization system **10** can include one or more wavelength-sensitive (e.g., dichroic) beam splitters **28** that can combine the light of different colors to form a single multi-color beam.

The visualization system **10** can direct the modulated light toward the eyes of the viewer in one of at least two configurations. In a first configuration, the visualization system **10** can function as a projector, and can include suitable projection optics **30** that can project the modulated light onto one or more screens **32**. The screens **32** can be located a suitable distance from an eye of the user. The visualization system **10** can optionally include one or more lenses **34** that can locate a virtual image of a screen **32** at a suitable distance from the eye, such as a close-focus distance, such as 500 mm, 750 mm, or another suitable distance. In some examples, the visualization system **10** can include a single screen **32**, such that the modulated light can be directed toward both eyes of the user. In some examples, the visualization system **10** can include two screens **32**, such that the modulated light from each screen **32** can be directed toward a respective eye of the user. In some examples, the visualization system **10** can include more than two screens **32**. In a second configuration, the visualization system **10** can direct the modulated light directly into one or both eyes of a viewer. For example, the projection optics **30** can form an image on a retina of an eye of the user, or an image on each retina of the two eyes of the user.

For some configurations of augmented reality systems, the visualization system **10** can include an at least partially transparent display, such that a user can view the user's surroundings through the display. For such configurations, the augmented reality system can produce modulated light that corresponds to the augmentation of the surroundings, rather than the surroundings itself. For example, in the example of a retailer showing a chair, the augmented reality system can direct modulated light, corresponding to the chair but not the rest of the room, toward a screen or toward an eye of a user.

FIGS. **3** and **4** show side-view drawings of the light source **100** of FIG. **1** in various stages of assembly. Assembling the light source **100** in this manner can help avoid air occlusions, which can degrade the appearance and optical performance of the finished device. Other assembly techniques can also be used.

In FIG. **3**, a sparse array of LEDs **102** has been disposed (e.g., mounted, grown, deposited, or otherwise formed) on the transparent flexible substrate **104**. The transparent flexible substrate **104** has been removably mounted in or on a frame **302**. Lamination tooling **304** can advance the frame **302** toward an adhesive layer **306** that has been deposited on a support film **308**. Alternatively, the lamination tooling **304** can advance the adhesive layer **306** toward the frame **302**, or advance both toward each other. The sparse array of LEDs **102** will contact the adhesive layer **306**, which has been deposited on the support film **308**. The adhesive of the adhesive layer **306** can be in solid form at room temperature. The adhesive has been coated on the support film **308** and has been covered by a cover film (not shown). A vacuum laminator with a temperature range that allows the adhesive to flow and conformally cover the LED array topography can laminate the adhesive layer **306** onto the sparse array of LEDs **102** to encapsulate the sparse array of LEDs **102** in the adhesive layer **108**. After lamination, the support film **308** can then be removed.

In FIG. **4**, the lamination tooling **404** (optionally the same lamination tooling **304** as in FIG. **3**) can advance the transparent flexible substrate **104** and the adhesive layer **108**, with the sparse array of LEDs **102** encapsulated in the adhesive layer **108**, toward the rigid substrate **106**. Alternatively, the lamination tooling **404** can advance the rigid substrate **106** toward the transparent flexible substrate **104** and the adhesive layer **108**, or advance both toward each other. The lamination tooling can laminate the adhesive layer **108**, with the sparse array of LEDs **102** encapsulated

in the adhesive layer **108**, onto the rigid substrate **106**. After the adhesive layer **108** has been laminated onto the rigid substrate **106**, the full layered structure can be subjected to a temperature cycle, exposure to ultraviolet light, or other suitable curing technique to cure the adhesive.

In the examples described above, the transparent flexible substrate **104** has been laminated with the LED side facing the rigid substrate **106**, such that the LEDs **102** are located between the two substrates and encapsulated by the adhesive. Alternatively, the transparent flexible substrate **104** can be laminated with the LED side facing away from the rigid substrate **106**, such that the LEDs **102** are exposed, and the transparent flexible substrate **104** is located between the exposed LEDs **102** and the rigid substrate **106**.

In some examples, additional components can be assembled onto the transparent flexible substrate, such as integrated circuits (ICs), micro-ICs, or transistors for display backplanes. Moreover, additional layers may be integrated into a device to form a capacitive or resistive touchscreen.

In some embodiments, an LED includes multiple semiconductor layers grown on a substrate (e.g., a sapphire substrate) that are to be fabricated into pixels. The substrate may be any substrate, such as sapphire, capable of having epitaxial layers grown thereon. The substrate may have patterns on which the epitaxial layers are grown. The pixels may be formed from gallium nitride (GaN), having an n-type semiconductor adjacent to the substrate, a p-type semiconductor, and an active region between the n-type semiconductor and the p-type semiconductor. The active region may be, for example, a multiple quantum well structure in which light is generated for emission from the pixels. After processing, the substrate may be removed in some embodiments.

Before etching of the epitaxial GaN layers, die layers of chip-scale packages (CSP) allowing uniform current distribution and optical coupling may be deposited or otherwise formed. For example, uniform current injection in the p-type semiconductor may be obtained by depositing a transparent conductive oxide (TCO) layer such as indium tin oxide (ITO), indium zinc oxide (IZO), zinc oxide (ZnO), or tin oxide (SnO) on the p-type semiconductor. Each of these TCO layers may be considered to be a transparent coating.

FIG. **5**A illustrates a cross-sectional view of an LED **500***a* of a sparse array, in accordance with some examples. The LED **500***a* may contain an epitaxial stack **510** of n-type and p-type semiconductors (e.g., GaN, InGaN, AlInGaP, GaAs, InGaAs). The thickness of the epitaxial stack **510** may range from about 3 μm to about 15 μm, typically about 5 μm. The n-type semiconductor and p-type semiconductor of the epitaxial stack **510** may make electrical contact to traces **514** on a substrate **516** via an n-contact **512***a* and a p-contact **512***b*, respectively. The n-contact **512***a* and p-contact **512***b* (or interconnect material) may be formed from a metal or compound such as Au, Sn, AuSn, In, Anisotropic conductive film (ACF)/ACInk, Self-Aligned Contact (SAC). The thickness of the contact **512***a* and p-contact **512***b* may range from about 0.02 μm to about 5 μm, typically about 0.1 μm. The traces **514** may be formed from a TCO material. The thickness of the traces **514** may range from about 0.5 μm to about 10 μm, typically about 1 μm. The n-contact **512***a* and p-contact **512***b* may be patterned and formed from a metal, such as copper (Cu), nickel (Ni), gold (Au), silver (Ag), and/or titanium (Ti), for example, which may be deposited on the epitaxial stack **510**. The substrate **516** may be the rigid or flexible substrate described above formed, for example, from glass, PET, polyamideimide, polyetherimide, or clear polyimide. The thickness of the substrate **516** may range from about 50 μm to about 1000 μm, typically about 100 μm. Metallic conductors **518** may make contact to the traces **514** to route power and other signals to the epitaxial stack **510**. The metallic conductors **518** may be formed from a metal or compound such as Au, Cu, Al, Ti, Ni, or Mo. The thickness of the metallic conductors **518** may range from about 0.5 μm to about 30 μm, typically about 1 μm.

In some embodiments, a light-converting layer **520** containing phosphor particles may be disposed on or adjacent to the epitaxial stack **510**. The light-converting layer **520** may convert the light emitted by the epitaxial stack **510** to white light, for example.

A lens **530** and/or other optical elements may be disposed over the epitaxial stack **510** as shown. The lens **530** and/or other optical elements may be incorporated in the adhesive layer. Although not shown, the other substrate may be disposed on the lens **530**.

FIG. **5**B illustrates a cross-sectional view of an LED **500***b* of another sparse array, in accordance with some examples. As indicated, the difference between the LED **500***b* of FIG. **5**B and the LED **500***a* of FIG. **5**A is the presence of a submount **522** (the optional light-converting layer **520** and lens **530** are not shown in FIG. **5**B for convenience). The submount **522** may be a rigid substrate formed, for example, from glass or silicon. The thickness of the submount **522** may range from about 5 μm to about 100 μm, typically about 20 μm. The interconnect material may be the same on both sides of the submount **522**.

In some embodiments, vertical singulated LEDs may have a smallest x-y dimensions of about 3 μm×about 3 μm and a largest x-y dimensions of about 15 μm×about 15 μm. Lateral and flip chip LEDs may have a smallest x-y dimensions of about 3 μm×about 6 μm and a largest x-y dimensions of about 50 μm×about 75 μm in various embodiments. In this case, a 127 μm×127 μm panel having a 200 pixels per inch (ppi) with a 40×40 μm microIC, 25×25 μm LED submount, 2×10 μm×127 μm traces to supply the microIC, 2×10 μm×<50 μm traces to supply LEDs, the total opaque or semi-opaque area of a tile is 5765 μm^2, the total area per pixel in 200 ppi is 16129 μm^2, and the fractional area is 35% covered, 65% transparent. Similarly, a 362 μm×362 μm panel having a 70 ppi with a 40×40 μm microIC, 25×25 μm LED submount, 2×10 μm×362 μm traces to supply the microIC, 2×10 μm×<150 μm traces to supply LEDs, the total opaque or semi-opaque area of the tile is 12465 μm^2, the total area per pixel in 70 ppi is 131044 μm^2, and the fractional area is 10% covered, 90% transparent. Either of these may provide panels with sufficient transparency to see through the panel. That is, in a sparse display, a distance between LEDs of the sparse array of LEDs permits display of at least one of alphanumeric and image information while providing visibility through the transparent material.

As above, displays have always had a viewing side that emits light and a side that is full of electronics and components that operate to create the light and images. Transparent displays enabled by microLEDs may have an emitting side and a backplane side. In some applications, it may be desirable to emit light from one side of the display and emit no light from a reverse side; in other applications, however, such a limitation may be impractical and true light leakage prevention be solved by means other than inherent design. In the current embodiments described herein, the surfaces ideal for transparent display integration may have utility outside in and inside out, and in many use cases, these are exclusive. Therefore, a display that can provide images of similar

quality from both sides can greatly enhance the utility of the display while efficiently using their size and integration effort.

FIG. **5**C illustrates a cross-sectional view of an LED of another sparse array, in accordance with some examples. The flip chip or lateral LED **500***c* of FIG. **5**C may be a microLED that emits substantially equivalently from both sides, meaning that there are transparent contacts and regions of both the n and p side of the structure to make electrical contact with the n and p side of the structure. As shown in FIG. **5**C, the LED **500***c* may contain a p-type semiconductor **532***a* and an n-type semiconductor **532***b* on opposing sides of an active region **532***c* that may include multiple quantum well structure. A transparent contact **534***a* may be disposed on the p-type semiconductor **532***a*. Similarly, a transparent protective coating **536** or pattern that mimics the transparent contact **534***a* may be formed on the n-type semiconductor **532***b*. The p-type semiconductor **532***a* and the active region **532***c* may be etched to expose a portion of the n-type semiconductor **532***b*. A transparent (or non-transparent) contact **534***b* may be formed on the exposed portion of the n-type semiconductor **532***b*. Thus, the display backplane may be substantially transparent, including the main emission area and a majority of electrical conduction traces connecting to the emission area. Examples of candidate materials include glass, PET, polyamideimide, polyetherimide, or clear polyimide for the substrate and ITO or ZnO for the electrically conducting traces. The transparent contacts may be, for example, very thin metals such as Ni at 50-80 Angstroms thickness. Other thin metals may also be used, such as Al, Ti, Au, Ag, Mo for example. An interconnect or bonding system for the LED to the backplane that is substantially transparent and has well controlled transmission may also be used.

Note that it may be desirable for the transmission % between the top and bottom of the LED to be roughly equivalent, regardless of the die type—as described vertical or lateral/flip chip. In the case of a flip chip LED, a broad contact (e.g., ITO/Ag) may be used on the mesa for the p contact, and, as the opposing side of the device may usually have no contact and thus no metal on that surface, a layer (the transparent protective coating **536** or pattern) may be used to make the transmission equivalent to the contacted surface. The transparent protective coating **536** or pattern may be similar to the actual contacting metals but may also be different (e.g., a metal or an oxide or a combination of the two may be used).

FIG. **5**D illustrates a cross-sectional view of an LED of another sparse array, in accordance with some examples. The vertical LED **500***d* of FIG. **5**D contains a p-type semiconductor **542***a* and an n-type semiconductor **542***b* on opposing sides of an active region **542***c* that may include multiple quantum well structure. A transparent contact **544***a*, **544***b* may be respectively disposed on the p-type semiconductor **542***a* and the n-type semiconductor **542***b*. As the active regions **532***c*, **542***c* of FIGS. **5**C and **5**D emit in all directions, light may be emitted from both the transparent contact and, if present, the coating in the structures of FIGS. **5**C and **5**D.

Although not shown, FIGS. **5**C and **5**D, other layers may be present, such as depositing or otherwise forming a reflective material on the sidewalls of the semiconductor structures to limit light emitted from the active region being emitted from an edge of the semiconductor structures. That is, substantially the entirety of the light emitted from the active region is emitted from a surface of the semiconductor structures in a growth direction of the semiconductor structures (i.e., in a direction between the transparent contacts). The reflective material may be formed from one or more metal layers (e.g., Cu), or a multilayer Bragg reflector structure containing, e.g., layers of oxide of different refractive indices.

FIG. **6** shows a top view of an example panel **600**. The panel **600** contains multiple adjacent (touching) tiles **602***a*, **602***b*. Each tile **602***a*, **602***b* contains an LED array **610**. Each LED array **610** contains multiple LEDs **612** arranged in a sparse distribution, similar to that described above. Each LED **612** may emit light of the same color or may emit different light of different colors. The electrical connections between the LEDs **612** and from LEDs **612** to other (external) components such as a driver are not shown for convenience. Multiple LEDs **612** of different colors may be arranged at each individual (pixel) location of the LEDs **612**.

As shown, the panel **600** may be formed from adjacent LED arrays **610** (tiles **602***a*, **602***b*). In some embodiments, each LED array **610** may be of the same size and may have the same number of LEDs **612**. The LEDs **612** within each LED array **610** may be separated by a uniform distance, or substantially uniform distance, D in both orthogonal (x-y) directions. Each LED **612** closest to the edge in each LED array **610** is disposed is disposed at half the uniform distance D/2 from the edge of the LED array **610**.

Although the LEDs **612** are shown in FIG. **6** as being disposed in a square LED array **610** (i.e., the number of LEDs **612** are the same in each orthogonal direction) any shaped LED array (e.g., rectangular, triangular) may be used in the panel **600** so long as the LED arrays are able to fit together to be in contact on all sides with another LED array and the spacing between the LEDs **612** remains constant. Drivers and other control circuitry may be disposed at one electronics edge **620** or opposing edges of each tile **602***a*, **602***b*. The electronics edge **620** may be orthogonal to a common edge between the tiles **602***a*, **602***b*. The electronics edge **620** may contain multiple drivers that are each configured to drive one or more microLEDs in each pixel.

Thus, a display formed by the panel **600** may essentially be edgeless. That is, at most three sides may be free from any visible power conductors or signal busses. Such a display may be formed from multiple tiles **602***a*, **602***b* having essentially identical characteristics and substantially uniform distance between pixels (LEDs) to form a larger display.

Although not shown, in some embodiments every panel or tile may contain one or more control components. The control components may include one or more sensors to detect users in proximity of the panel and/or tile and provide feedback to the processor. In addition, the panel or tile may include other sensors, such as touch sensors, to allow the panel or tile to be used as a user input device in addition to merely displaying information. In this case, the panel or tile may, for example, display an alphanumeric pad using the panel or tile on a side window that contains the sparse LED array (which display may be initiated based on a proximity sensor in the panel detecting the presence of a user). The panel or tile may also include one or more connectors to external digital signals, conductors and interfaces for power supply to the panel or tile, as well as other control circuitry. Integrated circuits that supply current to LEDs for one or more pixels may be included for every nth pixel. In addition, every pixel may include multiple LEDs of different colors (e.g., red, green, and blue LEDs), in addition to conductors for power and digital signals to enable delivery of a predetermined current to the LEDs.

FIG. **7** illustrates an example of a panel with a single tile. The panel **700** may include a single tile that has a sparse LED array **702**, an electronics edge **704**, and a connector **706** electrically coupled to the electronics edge **704**. The various components are described above. In an off mode, the panel **700** is transparent. The panel **700** may provide display on a single side or on opposite sides, as described herein.

FIGS. **8**A-**8**B illustrate an example of a panel with multiple display tiles. Similar to FIG. **7**, each tile of the panel **800***a*, **800***b* in FIGS. **8**A and **8**B may include a sparse LED array **802**, an electronics edge **804**, and a connector **806** electrically coupled to the electronics edge **804**. For the rectangular tiles shown in FIGS. **8**A-**8**B, in FIG. **8**A the electronics edge **804** of the panel **800***a* may be disposed along a single continuous edge that forms the long edge of each tile of the panel **800***a* (with the short edge being common between the rectangular tiles); in FIG. **8**B the electronics edge **804** of the panel **800***b* may be disposed along opposing edges that form the short edges of each tile of the panel **800***b* (with the long edge being common between the rectangular tiles). In an off mode, the panel **800***b* is transparent. The panel **800***b* may provide display on a single side or on opposite sides. In FIGS. **8**A and **8**B the tiles are the same size; in other embodiments the tiles may be different sizes, so long as the distance between pixels (that contain multiple different color LEDs) is the same.

FIGS. **9**A and **9**B show examples of a sparse LED array arrangement. As described herein, the dual-sided panel **900***a*, **900***b* (e.g., a dual-sided display) may contain a panel **914** that contains multiple sparse LED arrays **912***a*, **912***b* disposed back-to-back. The individual (or sets of pixels) of the sparse LED arrays **912***a*, **912***b*. Each of the sparse LED arrays **912***a*, **912***b* may be disposed on a non-transparent substrate, thereby limiting viewing of the information projected to only one hemisphere. A connection **918**, such as a cable or wiring, may provide power and enable control by a processor of the panel **914** via traces **916** connected to electronics of the panel **914** that control the sparse LED arrays **912***a*, **912***b*. As shown in FIG. **9**A, the panel **914** may be disposed within a cavity formed by the transparent material **910**. An end of the power connection **918** may be retained within the transparent material **910** to provide a robust electrical connection with the traces **916**. As shown in FIG. **9**B, the panel **914** may instead be disposed on the transparent material **910** and protected by a protective layer **920**, such as PET. The use of a dual-sided sparse LED array arrangement as described in FIGS. **9**A and **9**B may permit different information to be displayed to observers on opposite sides of the transparent material **910** without limiting viewing through the transparent material **910** in either direction.

FIG. **10** shows an example display. The display **1000** may include a display stack **1002** [APC1] that includes, for example, the LEDs shown in FIG. **5**C or **5**D in the sparse array in the panel shown in FIG. **6**. The display stack **1002** may thus include LEDs (such as microLEDs) that emit substantially equivalently from both sides of the display **1000**, as provided by the transparent contacts and regions of both the n and p side of the structure in FIG. **5**C or **5**D. In addition, the backplane of the display **1000** (not shown in FIG. **10**) may be substantially transparent, including the main area of emission (the area of the LED array) and a majority of electrically conductive traces that provide power and control to the LEDs of the array (and other components of the panel). The substrate may thus be formed from one or more materials such as glass, PET, polyamideimide, polyetherimide, or clear polyimide and the electrically conducting traces may be formed from one or more TCO materials such as ITO. An interconnect or bonding system for the LEDs to the backplane may also be substantially transparent.

A darkening layer **1004***a*, **1004***b* may be disposed on the outermost side of each side of the display stack **1002**. The darkening layer **1004***a*, **1004***b* may be disposed on the substantially transparent contacts or may be separate from the panel as a separate layer on the display **1000**. The darkening layer **1004***a*, **1004***b* may be selectable to darken (thereby providing selectable darkening) such that light is only emitted from one side of the display **1000**. The darkening layer **1004***a*, **1004***b* may be formed from, or may include, an electro-chromic material (thereby providing an electro-chromic structure in the disclosed subject-matter) that changes opacity in response to an electrical signal, thereby being able to provide, for example, electro-chromatic darkening. The electro-chromic material may also include a liquid crystal display (LCD), in which polarization of the liquid crystal in the cells is changed by 90° to block light (which may be polarized by a polarization film on the LED and/or on the side of the darkening layer **1004***a*, **1004***b* opposing the display stack **1002**) from the display stack **1002**. The activation of the darkening layer **1004***a*, **1004***b* on one side of the display **1000** may provide improved contrast for viewing light from the display stack **1002** on the opposite side of the display **1000**. In some embodiments, rather than using an electro-chromic material, an iris or other mechanically-activated layer may be used to provide the darkening layer **1004***a*, **1004***b*.

The darkening layer **1004***a*, **1004***b* may be controlled by a processor. The processor may be part of the panel or display **1000** or may be within the system of which the display **1000** is a part. In some embodiments, the entire area of the darkening layer **1004***a*, **1004***b* may be controlled by the processor as a single element, i.e., the entire darkening layer **1004***a*, **1004***b* may have the same state (transparent, opaque, or an intermediate state). In other embodiments, the darkening layer **1004***a*, **1004***b* may be segregated into multiple regions and the regions individually controlled by the processor.

In some embodiments, the darkening layer **1004***a*, **1004***b* may be controlled in response to sensor information. One or more sensors may provide the sensor information to the processor. Like the darkening layer **1004***a*, **1004***b*, the sensors may be integrated into the panel or display **1000** or may be within the system of which the display **1000** is a part.

The sensors may include a proximity sensor and/or a (capacitive) touch sensor. The proximity sensor and touch sensor may respectively enable presence detection and use detection to provide user experience. The proximity sensor may sense which side of the display **1000** that a user is on and correctly orient the display image. The proximity sensor may use infrared light to determine the presence of a user on one side of the display **1000**. The processor may determine the user presence for a predetermined amount of time (e.g., greater than about 5 seconds) and active the darkening layer **1004***a*, **1004***b* on the other side of the display **1000** as the user. Alternatively, the proximity sensor may include a camera and the processor may determine the user presence from facial recognition of images captured by the camera.

In general, each pixel in display **1000** may emit light in a direction symmetric around a normal direction that is normal to the underlying portion on which the pixel is disposed. In some embodiments, the light from each pixel may radiate in a Lambertian pattern, for example. However, propagation of the light in the normal direction may result in a diminished

viewing capacity for individuals not within the main lobe of the Lambertian pattern as a significant portion of the light is directed towards a direction that is not viewable. To this end, in some embodiments, one or more optical elements in the sparse array may be used to adjust the emission angle to an optimized direction in which the (Lambertian) pattern of the emitted light centers around a primary non-normal viewing angle for a viewing position based on the detected user location. Eye tracking information may also be used to adjust the light emission angle similar to augmented reality/virtual reality systems.

Alternatively, rather than the LEDs shown in FIG. **5**C or **5**D being used, in other embodiments, the dual-sided arrays shown in FIG. **9**A or **9**B may be used in the embodiment shown in FIG. **10**. In this case, as the arrays may be independently controlled, and thus able to show the same information or different information, the darkening layer **1004***a*, **1004***b* may or may not be present.

FIG. **11** shows an example system. The system **1100** may include one or more light sources **1110***a*, **1110***b*. A first light source **1110***a* may include one or more of the sparse LED arrays **1112** as described herein. The first light source **1110***a* may include local drivers **1114**, as also described herein. The first light source **1110***a* may be disposed in various locations on or within an apparatus, as described in more detail herein. A second light source **1110***b* may be present and may include one or more non-sparse LED arrays **1116** (e.g., microLED arrays, miniLEDs arrays, or other). The second light source **1110***b* may be disposed in various other locations on or within an apparatus containing the system **1100**.

The LEDs in the first light source **1110***a* and/or second light source **1110***b* may contain microLEDs. A microLED array contains thousands to millions of microscopic microLEDs that emit light and that may be individually controlled or controlled in groups of pixels (e.g., 5×5 groups of pixels). The microLEDs are small (e.g., <0.07 mm on a side) and may provide monochromatic or multi-chromatic light, typically red, green, blue, or yellow using inorganic semiconductor material such as that indicated above. Other LEDs may have a size, for example, of about 4 mm^2, 250 micron×250 micron, or larger. MicroLEDs may be used, for example, due to their thickness about a 5 μm thickness or so, similar to thin film LEDs, and, as there is no substrate inherent to microLEDs, microLEDs may be able to be placed directly on a backplane. This results in a light source that has an overall thickness that is substantially less than that using other LEDs. The individual control provided by the microLEDs allows the driving electronics for displays to use either an active matrix array of driving transistors or a full driver microICs individual intensity control. The use of microICs may be used to bring a substantial amount of fine control to each LED operation.

A controller **1130** may include a processor **1132**, which may be used to control various functions of the system **1100**. As also shown, the controller **1130** may contain further components, such as a driver **1134** configured to drive, among others, the second light source **1110***b* as controlled by the processor **1132**. In some embodiments, the driver **1134** may also be configured to provide non-local driving of the sparse LED arrays **1112** of the first light source **1110***a*.

As above, LEDs of the sparse LED arrays **1112** and non-sparse LED arrays **1116** may be formed from one or more inorganic materials (e.g., binary compounds such as gallium arsenide (GaAs), ternary compounds such as aluminum gallium arsenide (AlGaAs), quaternary compounds such as indium gallium phosphide (InGaAsP), gallium nitride (GaN), or other suitable materials), usually either III-V materials (defined by columns of the Periodic Table) or II-VI materials. The LEDs in the different arrays may emit light in the visible spectrum (about 400 nm to about 800 nm) and/or may emit light in the infrared spectrum (above about 800 nm). At least some of the LEDs may be formed by combining n- and p-type semiconductors on a rigid substrate (which may be textured), for example, of sapphire aluminum oxide (Al2O3) or silicon carbide (SiC), among others. In particular, various layers are deposited and processed on the substrate during fabrication of the LEDs. The surface of the substrate may be pretreated to anneal, etch, polish, etc. the surface prior to deposition of the various layers. The original substrate may be removed and replaced by a thin transparent rigid substrate, such as glass, or a flexible substrate, for example plastic.

In general, the various LED layers may be fabricated using epitaxial semiconductor deposition (e.g., by metal organic chemical vapor deposition) to deposit one or more semiconductor layers, metal deposition (e.g., by sputtering), oxide growth, as well as etching, liftoff, and cleaning, among other operations. The substrate may be removed from the LED structure after fabrication and after connection to contacts on a backplane via metal bonding such as via wire or ball bonding. The backplane may be a printed circuit board or wafer containing integrated circuits (ICs), such as a CMOS IC wafer. The semiconductor deposition operations may be used to create an LED with an active region in which electron-hole recombination occurs and the light from the LED is generated. The active region may be, for example, one or more quantum wells. Metal contacts may be used to drive provide current to the n- and p-type semiconductors from the ICs (such as drivers) of the backplane on which the LED is disposed. Methods of depositing materials, layers, and thin films may include, for example: sputter deposition, atomic layer deposition (ALD), chemical vapor deposition (CVD), physical vapor deposition (PVD), plasma enhanced atomic layer deposition (PEALD), plasma enhanced chemical vapor deposition (PECVD), and combinations thereof, among others.

In some embodiments, one or more other layers, such as a phosphor-converting layer that contains phosphor particles, may be disposed on some or all of the LEDs or some or all of the LED arrays **1112**, **1116** to convert at least a portion of the light from the LEDs to light of a different wavelength. For example, blue light from GaN LEDs may be converted into near infrared light or white light by the phosphor-converting layer.

The light sources **1110***a*, **1110***b* may include at least one lens and/or other optical elements such as reflectors. In different embodiments, a single lens may be disposed over one or more of the LED arrays **1112**, **1116**, multiple lenses may be disposed over one or more of the LED arrays **1112**, **1116** with a single lens disposed over one or more of the LED arrays **1112**, **1116**, or multiple lenses may be disposed over one or more of the LED arrays **1112**, **1116** with a single lens disposed over one or more of the LEDs of each of the LED arrays **1112**, **1116**. The at least one lens and/or other optical elements may direct the light emitted by the one or more of the LED arrays **1112**, **1116** toward a target.

The processor **1132** may also control a sensor **1120** that includes a multi-pixel detector **1122**. The sensor **1120** may sense light at the wavelength or wavelengths emitted by the second LED array **1116** and reflected by a target and/or radiation that is emitted by the target. The sensor **1120** may, for example, be a radar or lidar sensor, or the processor **1132** may be used to determine the presence of specific objects (e.g., other vehicles, people, road signs) nearby. The sensor

1120 may include optical elements (e.g., at least one sensor lens) to capture the radiation. The multi-pixel detector 1122 may include, for example, photodiodes or one or more other detectors capable of detecting light in the wavelength range (s) of interest.

The multi-pixel detector 1122 may include multiple different arrays to sense visible and/or infrared light. The multi-pixel detector 1122 may have one or more segments (that are able to sense the same wavelength/range of wavelengths or different wavelength/range of wavelengths), similar to the LED array 1116.

In some embodiments, instead of, or in addition to, being provided in the sensor 1120, a multi-pixel detector may be provided in the second light source 1110*b*. In some embodiments, the second light source 1110*b* and the sensor 1120 may be integrated in a single module, while in other embodiments, the second light source 1110*b* and the sensor 1120 may be separate modules that are disposed on a printed circuit board (PCB) or other mount. In other embodiments, the second light source 1110*b* and the sensor 1120 may be attached to different PCBs or mounts.

The LEDs in each of the LED arrays 1112, 1116 may be driven in an analog or digital manner, i.e., using a direct current (DC) driver or pulse width modulation (PWM). As shown, drivers 1114, 1134 may be used to respectively drive the LEDs in the LED array 1112, 1116, as well as other components, such as the actuators.

The components of the system 1100 shown in FIG. 10 may be provided power using a power supply 1140, such as a battery.

The first light source 1110*a* may be arranged to emit light in sparse distribution such that the LEDs occupy a small areal density so as to enable visual observation of information provided by the first light source 1110*a* while permitting viewing through the underlying transparent (flexible) substrate of the regions between the LEDs along a line of sight that passes through the regions between the LEDs. This may allow an observer on the emitting side of the first light source 1110*a* to view the information projected by first light source 1110*a* as well as the underlying scene. In other embodiments in which the underlying substrate is fully reflective to visible light or specularly reflective, the regions between the LEDs may not be viewable.

The information projected by first light source 1110*a* may be static or moving, similar to that able to be formed from a non-sparse light source. The LEDs of the first light source 1110*a* may be electrically connected using conductive traces on the substrate that are configured to provide drive current to the LEDs from the drivers 1114. As above, the conductive traces may be transparent and include one or more layers of TCO. The conductive traces, even if formed from a non-transparent metal, may be relatively narrow and spaced sufficiently far apart to permit visual observation through the substrate without substantial interference. The conductive traces may, for example, be less than about 110 μm wide. The LEDs may be connected in series or parallel via the conductive traces along each of a row and column to the edge or edges containing the control circuitry (and power supply) and may be addressed individually or in groups of LEDs. The drivers 1114 and other control devices in the first light source 1110*a* for each pixel may also be referred to as a microIC.

FIG. 12 illustrates an example of a general device in accordance with some embodiments. The device 1200 may be a vehicle-embedded display for example. Various elements may be provided on a backplane indicated above, while other elements may be local or remote. Examples, as described herein, may include, or may operate on, logic or a number of components, modules, or mechanisms.

Modules and components are tangible entities (e.g., hardware) capable of performing specified operations and may be configured or arranged in a certain manner. In an example, circuits may be arranged (e.g., internally or with respect to external entities such as other circuits) in a specified manner as a module. In an example, the whole or part of one or more computer systems (e.g., a standalone, client or server computer system) or one or more hardware processors may be configured by firmware or software (e.g., instructions, an application portion, or an application) as a module that operates to perform specified operations. In an example, the software may reside on a machine readable medium. In an example, the software, when executed by the underlying hardware of the module, causes the hardware to perform the specified operations.

Accordingly, the term "module" (and "component") is understood to encompass a tangible entity, be that an entity that is physically constructed, specifically configured (e.g., hardwired), or temporarily (e.g., transitorily) configured (e.g., programmed) to operate in a specified manner or to perform part or all of any operation described herein. Considering examples in which modules are temporarily configured, each of the modules need not be instantiated at any one moment in time. For example, where the modules comprise a general-purpose hardware processor configured using software, the general-purpose hardware processor may be configured as respective different modules at different times. Software may accordingly configure a hardware processor, for example, to constitute a particular module at one instance of time and to constitute a different module at a different instance of time.

The electronic device 1200 may include a hardware processor (or equivalently processing circuitry) 1202 (e.g., a central processing unit (CPU), a GPU, a hardware processor core, or any combination thereof), a memory 1204 (which may include main and static memory), some or all of which may communicate with each other via an interlink (e.g., bus) 1208. The memory 1204 may contain any or all of removable storage and non-removable storage, volatile memory or non-volatile memory. The electronic device 1200 may further include a display/light source 1210 such as the LEDs described above, or a video display, an alphanumeric input device 1212 (e.g., a keyboard), and a user interface (UI) navigation device 1214 (e.g., a mouse). In an example, the display/light source 1210, input device 1212 and UI navigation device 1214 may be a touch screen display. The electronic device 1200 may additionally include a storage device (e.g., drive unit) 1216, a signal generation device 1218 (e.g., a speaker), a network interface device 1220, one or more cameras 1228, and one or more sensors 1230, such as a global positioning system (GPS) sensor, compass, accelerometer, or other sensor such as those described herein. The electronic device 1200 may further include an output controller, such as a serial (e.g., universal serial bus (USB), parallel, or other wired or wireless (e.g., infrared (IR), near field communication (NFC), etc.) connection to communicate or control one or more peripheral devices (e.g., a printer, card reader, etc.). Some of the elements, such as one or more of the sparse arrays that provide the display/light source 1210 may be remote from other elements and may be controlled by the hardware processor 1202.

The storage device 1216 may include a non-transitory machine readable medium 1222 (hereinafter simply referred to as machine readable medium) on which is stored one or more sets of data structures or instructions 1224 (e.g.,

software) embodying or utilized by any one or more of the techniques or functions described herein. The instructions **1224** may also reside, completely or at least partially, within the memory **1204** and/or within the hardware processor **1202** during execution thereof by the electronic device **1200**. While the machine readable medium **1222** is illustrated as a single medium, the term "machine readable medium" may include a single medium or multiple media (e.g., a centralized or distributed database, and/or associated caches and servers) configured to store the one or more instructions **1224**.

The term "machine readable medium" may include any medium that is capable of storing, encoding, or carrying instructions for execution by the electronic device **1200** and that cause the electronic device **1200** to perform any one or more of the techniques of the present disclosure, or that is capable of storing, encoding or carrying data structures used by or associated with such instructions. Non-limiting machine-readable medium examples may include solid-state memories, and optical and magnetic media. Specific examples of machine-readable media may include: non-volatile memory, such as semiconductor memory devices (e.g., Electrically Programmable Read-Only Memory (EPROM), Electrically Erasable Programmable Read-Only Memory (EEPROM)) and flash memory devices; magnetic disks, such as internal hard disks and removable disks; magneto-optical disks; Random Access Memory (RAM); and CD-ROM and DVD-ROM disks.

The instructions **1224** may further be transmitted or received over a communications network using a transmission medium **1226** via the network interface device **1220** utilizing any one of a number of wireless local area network (WLAN) transfer protocols or a SPI or CAN bus. Example communication networks may include a local area network (LAN), a wide area network (WAN), a packet data network (e.g., the Internet), mobile telephone networks (e.g., cellular networks), Plain Old Telephone (POTS) networks, and wireless data networks. Communications over the networks may include one or more different protocols, such as Institute of Electrical and Electronics Engineers (IEEE) 802.11 family of standards known as Wi-Fi, IEEE 802.14 family of standards known as WiMax, IEEE 802.14.4 family of standards, a Long Term Evolution (LTE) family of standards, a Universal Mobile Telecommunications System (UMTS) family of standards, peer-to-peer (P2P) networks, a next generation (NG)/6^{th} generation (**6**G) standards among others. In an example, the network interface device **1220** may include one or more physical jacks (e.g., Ethernet, coaxial, or phone jacks) or one or more antennas to connect to the transmission medium **1226**.

Note that the term "circuitry" as used herein refers to, is part of, or includes hardware components such as an electronic circuit, a logic circuit, a processor (shared, dedicated, or group) and/or memory (shared, dedicated, or group), an Application Specific Integrated Circuit (ASIC), a field-programmable device (FPD) (e.g., a field-programmable gate array (FPGA), a programmable logic device (PLD), a complex PLD (CPLD), a high-capacity PLD (HCPLD), a structured ASIC, or a programmable SoC), digital signal processors (DSPs), etc., that are configured to provide the described functionality. In some embodiments, the circuitry may execute one or more software or firmware programs to provide at least some of the described functionality. The term "circuitry" may also refer to a combination of one or more hardware elements (or a combination of circuits used in an electrical or electronic system) with the program code used to carry out the functionality of that program code. In these embodiments, the combination of hardware elements and program code may be referred to as a particular type of circuitry.

The term "processor circuitry" or "processor" as used herein thus refers to, is part of, or includes circuitry capable of sequentially and automatically carrying out a sequence of arithmetic or logical operations, or recording, storing, and/or transferring digital data. The term "processor circuitry" or "processor" may refer to one or more application processors, one or more baseband processors, a physical central processing unit (CPU), a single- or multi-core processor, and/or any other device capable of executing or otherwise operating computer-executable instructions, such as program code, software modules, and/or functional processes.

The camera **1228** may sense light at least the wavelength or wavelengths emitted by the LEDs. The camera **1228** may include optical elements (e.g., at least one camera lens) that are able to collect reflected light of illumination that is reflected from and/or emitted by an illuminated region. The camera lens may direct the reflected light onto a multi-pixel sensor (also referred to as a light sensor) to form an image of on the multi-pixel sensor.

The processor **1202** may control and drive the LEDs via one or more drivers. For example, the processor **1202** may optionally control one or more LEDs in LED arrays independent of another one or more LEDs in the LED arrays, so as to illuminate an area in a specified manner.

In addition, the sensors **1230** may be incorporated in the camera **1228** and/or the light source **1210**. The sensors **1230** may sense visible and/or infrared light and may further sense the ambient light and/or variations/flicker in the ambient light in addition to reception of the reflected light from the LEDs. The sensors may have one or more segments (that are able to sense the same wavelength/range of wavelengths or different wavelength/range of wavelengths), similar to the LED arrays.

FIGS. **13**A-**13**G illustrate an example of a process **1300** of fabricating the sparse array in accordance with some embodiments. FIG. **14** illustrates an example of a method **1400** of fabricating the sparse array in accordance with the process operations shown in FIGS. **13**A-**13**G. With concurrent reference to FIGS. **13**A-**13**G and FIG. **14**, the process starts in FIG. **13**A with a transparent flexible sheet **1302**. At operation **1402** in FIG. **14**, the transparent flexible sheet **1302** may be attached to a carrier wafer **1304** (or other type of carrier substrate) as depicted in FIG. **13**B. At operation **1404**, metal traces **1306** may be deposited on the transparent flexible sheet **1302** as shown in FIG. **13**C. At operation **1406**, the LED array **1308** may be assembled on the metal traces **1306** as shown in FIG. **13**D. At operation **1408**, the transparent flexible sheet **1302** containing the metal traces **1306** and the LED array **1308** may be released from the carrier wafer **1304** as shown in FIG. **13**E. At operation **1410**, an adhesive layer **1310** may be laminated on the transparent flexible sheet **1302** to cover the metal traces **1306** and the LED array **1308** as shown in FIG. **13**F. At operation **1412**, the transparent flexible sheet **1302** may be flipped and laminated onto a printed circuit board **1312** as shown in FIG. **13**G.

In other embodiments, a backplane with traces may be formed on the transparent substrate. The sparse LED array (which may contain microLEDs) may be transferred onto the transparent substrate with the backplane. The transfer may be performed, for example, using a mass transfer process to provide the sparse LED array. The mass transfer may be used to deposit the microLEDs (and microIC) mass on the transparent substrate by picking the location with

stamps and tethering or anchoring the transferred material using an adhesive layer, for example. The transfer may be performed, in another example, using one or more print nozzles arrayed in parallel to provide the sparse LED array in a vacuum nozzle transfer process. The print nozzles may be an ENJET tool adapted for this process. The laminated structure may then be formed in either case. In other embodiments, after transfer, specific microLEDs may be repaired or replaced using the ENJET Tool.

Alternatively, traces may be formed on the transparent substrate. The LEDs may then be formed on the transparent substrate and the laminated structure formed as above.

FIG. **15** illustrate an example of a process of operating a VR headset in accordance with various embodiments of the disclosed subject-matter. During the process **1500**, the VR headset is provided at operation **1502**. At operation **1504**, the opacity of a darkening layer in the VR headset may be changed based on VR interaction or potential collision. This is described in more detail below in relation to FIG. **17**.

Although sparse arrays are discussed in detail herein, in other embodiments the use of microLEDs having the structure described in FIG. **5**C or **5**D may be used in non-sparse arrays to provide similar displays as those described above, e.g., as shown in FIG. **10**.

FIG. **16** shows a block diagram of an example of a system in accordance with various embodiments of the disclosed subject-matter. The system **1600** may provide AR/VR functionality using microLEDs. The system **1600** can include a wearable housing **1612**, such as a headset or goggles. The wearable housing **1612** can mechanically support and house the elements detailed below. In some examples, one or more of the elements detailed below may be included in one or more additional wearable housings that can be separate from the wearable housing **1612** and couplable to the wearable housing **1612** wirelessly and/or via a wired connection. For example, a separate wearable housing may reduce the weight of wearable goggles, such as by including batteries, radios, and other elements. The wearable housing **1612** may include one or more batteries **1614**, which can electrically power any or all of the elements detailed below. The wearable housing **1612** may include circuitry that can electrically couple to an external power supply, such as a wall outlet, to recharge the batteries **1614**. The wearable housing **1612** may include one or more radios **1616** to communicate wirelessly with a server or network via a suitable protocol, such as WiFi.

The system **1600** may include one or more sensors **1618**, such as optical sensors, audio sensors, tactile sensors, thermal sensors, gyroscopic sensors, time-of-flight sensors, triangulation-based sensors, proximity sensors, eye-tracking sensors, and others. In some examples, one or more of the sensors can sense a location, a position, and/or an orientation of a user. In some examples, one or more of the sensors **1618** can produce a sensor signal in response to the sensed location, position, and/or orientation of the wearer. The sensor signal can include sensor data that corresponds to a sensed location, position, and/or orientation. For example, the sensor data may include a depth map of the surroundings. In some examples, such as for an AR system, one or more of the sensors **1618** can capture a real-time video image of the surroundings proximate a user.

The system **1600** may include one or more video generation processors **1620**. The one or more video generation processors **1620** can receive scene data that represents a three-dimensional scene, such as a set of position coordinates for objects in the scene or a depth map of the scene. This data may be received from a server and/or a storage medium. The one or more video generation processors **1620** can receive one or more sensor signals from the one or more sensors **1618**. In response to the scene data, which represents the surroundings, and at least one sensor signal, which represents the location and/or orientation of the user with respect to the surroundings, the one or more video generation processors **1620** can generate at least one video signal that corresponds to a view of the scene. In some examples, the one or more video generation processors **1620** may generate two video signals, one for each eye of the user, that represent a view of the scene from a point of view of the left eye and the right eye of the user, respectively. In some examples, the one or more video generation processors **1620** may generate more than two video signals and combine the video signals to provide one video signal for both eyes, two video signals for the two eyes, or other combinations.

The system **1600** may include one or more light sources **1622** that provide light for a display of the system **1600**. Suitable light sources **1622** may include the microLEDs above, for example. The one or more light sources **1622** may include light-producing elements having different colors or wavelengths. For example, a light source may include a red light-emitting diode that emits red light, a green light-emitting diode that emits green light, and a blue light-emitting diode that emits blue right. The red, green, and blue light combine in specified ratios to produce any suitable color that is visually perceptible in a visible portion of the electromagnetic spectrum. Each pixel of the system may include 3 or more microLEDs (such as a white emitting microLEDs, in which a wavelength-converting layer that contains phosphor particles converts the light from the microLED to white light).

The system **1600** can include one or more modulators **1624**. The modulators **1624** may be implemented in one of at least two configurations. In a first configuration, the modulators **1624** may include circuitry that modulate the light sources **1622** directly. For example, the light sources **1622** may include an array of LEDs (such as microLEDs), and the modulators **1624** may directly modulate the electrical power, electrical voltage, and/or electrical current directed to each light-emitting diode in the array to form modulated light. The modulation may be performed in an analog manner (current) and/or a digital manner (PWM). In some examples, the light sources **1622** may include an array of red light-emitting diodes, an array of green light-emitting diodes, and an array of blue light-emitting diodes, and the modulators **1624** may directly modulate the red light-emitting diodes, the green light-emitting diodes, and the blue light-emitting diodes to form the modulated light to produce a specified image.

In a second configuration, the modulators **1624** may include a modulation panel, such as a liquid crystal panel. The light sources **1622** may produce uniform illumination, or nearly uniform illumination, to illuminate the modulation panel. The modulation panel can include pixels. Each pixel can selectively attenuate a respective portion of the modulation panel area in response to an electrical modulation signal to form the modulated light. In some examples, the modulators **1624** may include multiple modulation panels that modulate different colors of light. For example, the modulators **1624** may include a red modulation panel that attenuates red light from a red light source such as a red light-emitting diode, a green modulation panel that attenuates green light from a green light source such as a green light-emitting diode, and a blue modulation panel that attenuates blue light from a blue light source such as a blue light-emitting diode.

In some examples of the second configuration, the modulators **1624** may receive uniform white light or nearly uniform white light from a white light source, such as a white-light light-emitting diode. The modulation panel may include wavelength-selective filters on each pixel of the modulation panel. The panel pixels may be arranged in groups (such as groups of three or four), where each group forms a pixel of a color image. For example, each group may include a panel pixel with a red color filter, a panel pixel with a green color filter, and a panel pixel with a blue color filter. Other suitable configurations can also be used.

The system **1600** may include one or more modulation processors **1626**, which receive a video signal, such as from the one or more video generation processors **1620**, and, in response, produce an electrical modulation signal. For configurations in which the modulators **1624** directly modulate the light sources **1622**, the electrical modulation signal may drive the light sources **1622**. For configurations in which the modulators **1624** include a modulation panel, the electrical modulation signal may drive the modulation panel.

The system **1600** may include one or more beam splitters **1628** (also known as beam combiners), which combine light beams of different colors to form a single multi-color beam. For configurations in which the light sources **1622** may include multiple light-emitting diodes of different colors, the system **1600** may include one or more wavelength-sensitive (e.g., dichroic) beam splitters **1628** that combine the light of different colors to form a single multi-color beam.

The system **1600** may direct the modulated light toward the eyes of the viewer in one of at least two configurations. In a first configuration, the system **1600** may function as a projector, and may include suitable projection optics **1630** that project the modulated light onto one or more screens **1632**. The screens **1632** may be located a suitable distance from an eye of the user. The system **1600** may optionally include one or more lenses **1634** that can locate a virtual image of a screen **1632** at a suitable distance from the eye, such as a close-focus distance, such as 500 mm, 750 mm, or another suitable distance. In some examples, the system **1600** may include a single screen **1632**, such that the modulated light may be directed toward both eyes of the user. In some examples, the system **1600** may include two screens **1632**, such that the modulated light from each screen **1632** may be directed toward a respective eye of the user. In some examples, the system **1600** may include more than two screens **1632**. In a second configuration, the system **1600** may direct the modulated light directly into one or both eyes of a viewer. For example, the projection optics **1630** may form an image on a retina of an eye of the user, or an image on each retina of the two eyes of the user.

For some configurations of AR systems, the system **1600** may include at least a partially transparent display, such that a user may view the user's surroundings through the display. For such configurations, the AR system may produce modulated light that corresponds to the augmentation of the surroundings, rather than the surroundings itself. For example, in the example of a retailer showing a chair, the AR system may direct modulated light, corresponding to the chair but not the rest of the room, toward a screen or toward an eye of a user.

FIG. **17** illustrates an example VR headset in accordance with various embodiments of the disclosed subject-matter. The VR headset **1700** may include a number of components as above. The VR headset **1700** may isolate the user from the real world and stimulate the user's visual senses with a virtual world generated in front of the user's eyes. One aspect of maintaining the illusion of the virtual world is to completely block out optical signals from the real world through the use of a completely opaque screen to allow the user to enjoy an immersive VR experience. The VR headset **1700** may be provided in any of a number of form factors, such as goggles or a helmet, for example.

The VR headset **1700** may include a frame **1710** on which multiple components may be disposed. The frame **1710** may be formed from a high impact-resistant opaque material such as acrylonitrile butadiene styrene (ABS), high-density polyethylene (HDPE), or polycarbonate, for example.

The components may include one or more sensors, such as a proximity sensor **1712**, a darkening layer **1714**, a display **1716**, and components **1718** that provide additional functionality. The darkening layer **1714**, display **1716**, and components **1718** may, in some embodiments, form a layer stack. The additional functionality may in addition or instead be introduced via one or more other transparent microLED arrays that are positioned in front or behind the display **1716**. The display **1716** may be formed from microLEDs transferred onto a backplane, and use narrow traces to maintain a high degree of transparency due to the small size and relative pitch of the microLEDs as above. The display **1716** may contain a sparse array or non-sparse array such as those described in FIG. **5**C or **5**D, for example.

The darkening layer **1714** may be similar to the darkening layer **1004***a*, **1004***b* of FIG. **10** and thus may have a controllable opacity. The darkening layer **1714** may, for example, be an LCD layer that is controlled by a processor **1718***a* in the components **1718**. The display **1716** may be more proximate to a user (center location **1720**) and thus more distal from the frame **1710** than the darkening layer **1714**. For example, the darkening layer **1714** may be disposed between the display **1716** and the frame **1710**. Alternatively, the darkening layer **1714** incorporated in the frame **1710** itself or the frame **1710** may be disposed between the display **1716** and the darkening layer **1714** (i.e., the darkening layer **1714** may be disposed on the outside of the frame **1710** and protected by a protective overlayer).

The darkening layer **1714** may be controlled to adjust the opacity. For example, when the darkening layer **1714** is fully opaque, the VR headset **1700** may act as a standard VR headset, allowing the user to enjoy an immersive VR experience. However, the darkening layer **1714** may be adjusted to become transparent and the VR image turned off, immediately transporting the user from the virtual world back into the real world (allowing the user to see through the transparent display **1716** through the transparent darkening layer **1714** to the real world), without removing the VR headset **1700**. The opacity of the darkening layer **1714** may be adjusted in a predetermined number of degradations between opaque and transparent. That is, the darkening layer **1714** may have a plurality of modes, including an opaque mode in which external light is blocked from the user and VR images are provided to the user by the display **1716**, and a transparent mode in which the user is able to see through the display **1716** to the outside and VR images are not supplied by the display **1716**.

The opacity adjustment of the darkening layer **1714** may be a safety feature, if combined, for example, with collision detection. One or more proximity sensors **1712** may be used for collision detection. The proximity sensors **1712** may be disposed at one or more sides of the frame **1710**. To this end, the proximity sensors **1712** may emit/detect infrared light or may periodically capture images. The periodicity of determining potential collisions may be predetermined (e.g., every few seconds) or may be dependent on whether the user is moving (as well as the speed and whether objects were

detected in a previous image capture) as determined by motion and orientation sensors in the components **1718**. Thus, if the user is not moving, the period may be extended or infinite to save battery life of a battery that supplies power to the VR headset **1700**. The detected infrared light or images may be processed by the processor **1718***a* to determine whether a potential collision with a real word object is likely. The determination of collision likelihood may be, as above, based on speed and direction of movement of the user, as well as distance to (and speed of) a detected object.

Once a potential collision is detected as being likely (e.g., greater than a predetermined percent, such as 60%), the processor **1718***a* may automatically adjust the darkening layer **1714** to be transparent and simultaneously deactivate the VR image provided by the display **1716**. Alternatively, the processor **1718***a* may control the display **1716** to replace a portion of the VR image projected by the display **1716** or to overlay an alert that a collision is immanent on the VR image.

In this alternative case (display of the alert), the processor **1718***a* may control the darkening layer **1714** to become transparent after providing the alert or may wait until a user input is provided. The user input may be a manual input on the frame **1710**. Alternatively, the processor **1718***a* may control the display **1716** to insert the user input onscreen (e.g., a corner of the display). Note that the use of independently controllable microLEDs may enable other areas of the VR display to be used to provide alphanumeric information (such as time/date, temperature, and notifications, among others). Such alphanumeric information, as well as the placement, may be controllable by the user through a VR user input or remotely (e.g., using a smartphone app, for example).

The components **1718** may include an infrared emitter and detector for eye tracking (i.e., an eye tracker **1718***b*) for the VR response as well as for controlling the opacity of the darkening layer **1714** via the onscreen user input (eye-gesture based control). That is, the processor **1718***a* may control the display **1716** to provide a virtual user input, determine whether the eye movement meets a predetermined criteria, and change the opacity of the darkening layer and deactivate display of a VR image by the display **1716** in response to a determination that the eye movement meets the predetermined criteria. The eye tracker and processor **1718***a* may determine whether the eye is open or closed and, if the eye is open, the determine a gaze direction of the eye. For example, the eye tracker and processor **1718***a* may detect that the user is focusing on the user input to change the opacity for a predetermined amount of time (2-3 seconds) and act to change the opacity in response. Alternatively, rather than an onscreen user input, the predetermined criteria may include a predetermined eye gesture, such as a double or triple blink or extended wink.

In another use case, in a modern office, the VR headset **1700** may display a virtual image of a user's work screen (in lieu of a computer display) on which the user performs work. If the user looks away from the virtual screen provided by the display **1716** for example to interact with colleagues (by moving their eyes or turning their head to face the colleagues for example), the opacity of the VR headset **1700** may adjusted to be transparent. Thus, the predetermined criteria above may be a movement that is dependent on the VR image provided by the display **1716**.

FIG. **18** illustrates another example VR headset in accordance with various embodiments of the disclosed subject-matter. The VR headset **1800** may include the layer stack **1802** described above covering or integrated with the frame **1810**. While the VR headset **1800** is shown as having a goggle shape, the VR headset **1800** may be any suitable shape. The microLEDs **1820** may be arranged in a central (rectangular) array **1822** and in a peripheral group **1824**, which may be formed in a circle or oval (e.g., mimicking the shape of an eye). In some embodiments, at least some microLEDs **1820** may emit infrared light to track the eye motion and gaze direction, while others of the microLEDs **1820** may emit visible light. The infrared emitting microLEDs may include a first set of microLEDs that provide constant illumination of the eye and another set of microLEDs may provide modulated illumination of the eye for eye tracking.

In some embodiments, the backplane that connects the microLEDs **1820** may have conductive traces to provide power to the microLEDs **1820**. For example, the microLEDs **1820** may be arranged in pairs, with the microLEDs **1820** in a pair electrically connected in parallel to provide redundancy in the event one of the microLEDs is defective or fails. The pairs of microLEDs **1820** may be arranged in multiple (e.g., two) strings in which each string has multiple (e.g., four) pairs of parallel connected the microLEDs **1820** connected in series by the conductive traces.

A laminated structure may be used to fabricate the microLEDs **1820**. In some embodiments, sets of the microLEDs **1820** may be disposed on a flexible transparent sheet (e.g., polymer). Conductive paths configured to power the microLEDs **1820**, a transparent substrate, and a transparent sheet of adhesive may be positioned between and bonded to the flexible transparent sheet and the transparent substrate. The microLEDs **1820** and conductive paths may be arranged to form a plurality of transparent microLED light sources for the VR headset **1800**, which may be separated from the laminated structure into individual components for the VR headset **1800**.

In some embodiments, the microLEDs **1820** may be disposed on a flexible transparent sheet with electrically conductive traces. The microLEDs **1820** may be formed directly on the transparent sheet, typically with the transparent sheet supported by an underlying rigid support. Alternatively, the microLEDs **1820** may be transferred to and attached to the transparent sheet. A layer of adhesive may be applied to one or both of the flexible transparent sheet and a rigid layer. The adhesive, such as silicone or polyimide for example, may be applied to the transparent sheet and the microLEDs **1820** thereon. The rigid substrate may be flat or curved or otherwise non-planar (e.g., faceted). The transparent sheet and the rigid layer may be brought together to form a laminated structure that is transparent to visible light, with the microLEDs **1820** and the adhesive between the layers. In some embodiments, the adhesive may be cured or cross-linked to effect adhesion of the layers.

If the rigid layer is curved (e.g., if the rigid layer forms a curved lens or a curved visor or faceplate of a helmet or headset), the flexible transparent sheet may be deformed to conform to the curved shape of the rigid layer. This enables attachment of the microLEDs **1820** to a rigid layer of any desired shape while enabling fabrication of the microLEDs **1820** on a planar wafer or substrate.

The adhesive may adhere the layers together and at least partly encapsulates the microLEDs **1820** between the layers. When conforming the flexible transparent sheet to the shape of the rigid layer (whether flat, curved, other otherwise nonplanar), attachment of the layers together may include taking steps to prevent, avoid, or eliminate bubbles or voids between the rigid layer and the transparent sheet.

The flexible transparent sheet may remain in its flexible or deformable state after attachment to the rigid layer. The transparent sheet may be cured or cross-linked after being positioned on and conformed to the rigid substrate. For example, the cured or cross-linked transparent sheet may be rigid after curing or cross-linking or may remain flexible, pliable, or compressible. The transparent sheet may also self-adhere to the rigid layer, i.e., acting as its own adhesive. The transparent sheet, as above, may include one or more materials including PI, PEN, PET, or other flexible or curable transparent polymer. The rigid layer may include one or more materials among silica, optical glasses, polycarbonate, PMMA, other rigid transparent polymers, or other rigid transparent materials.

FIG. **19** illustrates an example VR headset in accordance with various embodiments of the disclosed subject-matter. The VR headset **1900** may be similar to the VR headset **1700** shown in FIG. **17**. That is, the VR headset **1900** may include a frame **1910** on which multiple components may be disposed. The components may include one or more sensors, such as a proximity sensor **1912**, a darkening layer **1914**, a display **1916**, and components that provide additional functionality, such as a lens **1918***a*.

The display **1916** (as the display **1716**) may include a number of layers. In some embodiments, the darkening layer **1914** may be the outermost layer of the display **1916**. The darkening layer **1914** may include an electro-chromatic material, LCD, or e-ink, among others. The thickness of the darkening layer **1914** may range from about 15 μm to about 500 μm, typically about 50 μm. The darkening layer **1914** may be attached to a transparent substrate using a transparent adhesive. The transparent adhesive may include silicone, siloxane, epoxy-silicone hybrid, epoxy, or acrylic, among others. The thickness of the transparent adhesive may range from about 2 μm to about 100 μm, typically about 10 μm. The transparent substrate may include Glass, PET, or Clear PI, among others. The thickness of the transparent substrate may range from about 50 μm to about 1000 μm, typically about 100 μm. One of the transparent substrates may be a dummy backplane for mechanical support.

The microLED array may be embedded in a conformal transparent adhesive. The conformal transparent adhesive may include silicone, siloxane, epoxy-silicone hybrid, epoxy, or acrylic, among others. The thickness of the conformal transparent adhesive may range from about 10 μm to about 100 μm, typically about 25 μm. Each microLED may include GaN, InGaN, AlInGaP, GaAs, or InGaAs (i.e., light emitting semiconductors). The thickness of the microLED may range from about 3 μm to about 15 μm, typically about 5 μm.

The microLED may be attached to a transparent oxide conductor via an interconnect metal. The interconnect metal may include Au, Sn, AuSn, In, ACF/ACInk, or SAC, among others. The thickness of the interconnect metal may range from about 0.02 μm to about 5 μm, typically about 0.1 μm. The transparent oxide conductor may include ITO, ZnO, or SnO, among others. The thickness of the transparent oxide conductor may range from about 0.5 μm to about 10 μm, typically about 1 μm.

The display **1916** may be more proximate to a user (center location **1920**) and thus more distal from the frame **1910** than the darkening layer **1914**. The darkening layer **1914** may be controlled to adjust the opacity between transparent and opaque. When the darkening layer **1914** is fully opaque, the VR headset **1900** may act as a standard VR headset, allowing the user to enjoy an immersive VR experience. However, the darkening layer **1914** may be adjusted to become transparent and the VR image turned off, immediately transporting the user from the virtual world back into the real world (allowing the user to see through the transparent display **1916** through the transparent darkening layer **1914** to the real world), without removing the VR headset **1900**. The opacity of the darkening layer **1914** may be adjusted in a predetermined number of degradations between opaque and transparent.

One or more proximity sensors **1912** may be used for collision detection. The proximity sensors **1912** may be disposed at one or more sides of the frame **1910**. The detected infrared light or images obtained by the proximity sensors **1912** may be processed by a processor to determine whether a potential collision with a real word object is likely.

In this alternative case (display of the alert), the processor may control the darkening layer **1914** to become transparent after providing the alert or may wait until a user input is provided. The user input may be a manual input on the frame **1910**. Alternatively, the processor may control the display **1916** to insert the user input onscreen (e.g., a corner of the display) as described above.

In some embodiments, an artificial intelligence (AI) system may be used to determine collision likelihood. The AI system may, for example, look at the rate of change of proximity of the object to determine the collision probability. The likelihood threshold may be predetermined (e.g., within 0.5 meters of the VR headset **1900** or the threshold may be user set. Once a potential collision is detected as being likely, the processor may automatically adjust the darkening layer **1914** to be transparent and simultaneously deactivate the VR image provided by the display **1916**. Alternatively, the processor may control the display **1916** to replace a portion of the VR image projected by the display **1916** or to overlay an alert that a collision is immanent on the VR image.

An infrared emitter and detector may be used for eye tracking for the VR response as well as for controlling the opacity of the darkening layer **1914** via the onscreen user input (eye-gesture based control). The processor may control the display **1916** to provide a virtual user input, determine whether the eye movement meets a predetermined criteria, and change the opacity of the darkening layer and deactivate display of a VR image by the display **1916** in response to a determination that the eye movement meets the predetermined criteria. The eye tracker and processor may determine whether the eye is open or closed and, if the eye is open, the determine a gaze direction of the eye.

In another use case, in a modern office, the VR headset **1900** may display a virtual image of a user's work screen (in lieu of a computer display) on which the user performs work. If the user looks away from the virtual screen provided by the display **1916** for example to interact with colleagues (by moving their eyes or turning their head to face the colleagues for example), the opacity of the VR headset **1900** may adjusted to be transparent. Thus, the predetermined criteria above may be a movement that is dependent on the VR image provided by the display **1916**.

The lens **1918***a* may be, for example, a Fresnel lens. The lens may locate an image of the display **1916** at a suitable distance from the eye, such as at infinity or at a suitable viewing distance away from the eye, such as 0.5 m, 1 m, or others. In this case, another lens **1918***b* may be disposed after the display **1916** (i.e., on the opposite side of the display **1916** as the lens **1918***a*) to effectively undo the focusing effect of the lens **1918***a*, so that the real world appears as it commonly viewed. For example, if the lens **1918***a* is a positive lens, the other lens **1918***b* on the opposite

side of the display **1916** may be a negative lens, optionally with an equal but opposite amount of optical power. Similarly, if the lens **1918***a* is a negative lens, the other lens **1918***b* on the opposite side of the display **1916** may be a positive lens, optionally with an equal but opposite amount of optical power. As shown, the other lens **1918***b* may be disposed between the display **1916** and the darkening layer **1914**. In other embodiments, the darkening layer **1914** may be disposed between the display **1916** and the other lens **1918***b*. In some embodiments, the lens **1918***a* and the other lens **1918***b* may be part of the display stack. In other embodiments, the other lens **1918***b* may be disposed on the frame **1910**.

In some embodiments, the darkening layer **1914** may be separated into segments. The segments of the darkening layer **1914** may, for example, conform to the viewing area of the VR headset **1900**. That is, if viewing area of the VR headset **1900** are substantially circular, the segments of the darkening layer **1914** may be concentric rings. The processor may be able alter the opacity of the segments individually, which may be particularly useful for object avoidance. More specifically, as a significant amount of information is obtained using peripheral vision, as an object enters the frame of the proximity sensor **1912**, the processor may alter the opacity of the outermost concentric ring to be transparent and adjust the VR display to avoid use of the transparent portion of the darkening layer **1914**. This allows the real world field of view of the user to gradually expand as the object becomes increasingly proximate. The number and position of the segments may be predetermined or user set, allowing greater flexibility. The opening of the darkening layer **1914** by the processor may serve as an automatic collision warning to the user without the VR headset **1900** providing an explicit warning to the user.

FIG. **20** illustrates an example VR headset in accordance with various embodiments of the disclosed subject-matter. The VR headset **2000** may be similar to the VR headset **1900** shown in FIG. **19**. Most of the individual components are not reiterated for the sake of brevity, with the VR headset **2000** including a frame **2010**, a proximity sensor **2012**, a darkening layer **2014***a*, **2014***b*, a display **2016**, and lenses **2018***a*, **2018***b* disposed in similar manner with respect to the user (center location **2020**).

The lens **2018***a* and the other lens **2018***b* may be configured to provide optical adjustment and disposed in a manner similar to that described in relation to FIG. **19**. The darkening layer **2014***a*, **2014***b* also may be separated into segments. The segments of the darkening layer **2014***a*, **2014***b* may, for example, conform to the viewing area of the VR headset **2000**. That is, if viewing area of the VR headset **2000** are substantially circular, the segments of the darkening layer **2014***a*, **2014***b* may be concentric rings. The processor may be able alter the opacity of the segments individually based on information from the proximity sensor **2012** as described above. Unlike the VR headset **1900**, however, the darkening layer **2014***a*, **2014***b* of the VR headset **2000** may be a coating on the other lens **2018***b*. the darkening layer **2014***a*, **2014***b* may be disposed on one or both surfaces of the other lens **2018***b* (e.g., the inner surface more proximate to the display **2016** than the front of the frame **2010** and/or the outer surface more distal from the display **2016** than the front of the frame **2010**). In the example shown in FIG. **20**, based on the information from the proximity sensors **2012**, the processor has controlled the darkening layer **2014***a*, **2014***b* disposed on the outer surface of the other lens **2018***b* such that the inner portion of the darkening layer **2014***a* remains opaque while the outer portion of the darkening layer **2014***b* is transparent.

In the various embodiments of the VR headset described above, multiple lenses having different focal lengths may be used. The processor may be able to select a desired focal length dependent on a particular mode (e.g., VR, real world), as well as to correct for a user's vision issues (e.g., nearsighted, farsighted, astigmatic). Other optical elements may be used to partially compensate for viewable areas of the VR image and/or the real world. In some embodiments, the processor may mechanically shift lenses in the VR headset, e.g., either by autofocusing the lens along the viewing axis or along an axis perpendicular to the viewing axis. This may allow selection of a particular lens, or adjustment from a compensating optic to no optic being used, for example.

In other embodiments, the VR headsets above may use image recognition of a particular object within the view of the user to adjust the opacity of only segments of the darkening layer corresponding to the particular object. For example, the AI system may determine that the user is attempting to view an electronic device (e.g., smart phone, watch, laptop) and make the corresponding segments of the darkening layer transparent to allow the user to actually view the object in the real world. This may avoid the use of excessive processing after detection of the particular object create a virtual version of the particular object and create an overlay of the particular object (instead merely making the particular segment(s) transparent). The remaining segments may continue to provide the VR image.

EXAMPLES

Example 1 is a virtual reality (VR) headset comprising: a frame configured to receive a head of a user; a substantially transparent display that includes a sparse array of micro light-emitting diodes (microLEDs) configured to display a VR image; and a darkening layer having a controllable opacity, the darkening layer disposed between a front of the frame and the substantially transparent display.

In Example 2, the subject matter of Example 1 includes, wherein the microLEDs are configured to provide light to be viewed on opposing sides of the substantially transparent display, a distance between the microLEDs is configured to provide visibility through the array.

In Example 3, the subject matter of Examples 1-2 includes, a proximity sensor configured to detect a potential collision of the VR headset with an object; and a processor configured to change the opacity of the darkening layer from substantially opaque to substantially transparent in response to detection of the potential collision.

In Example 4, the subject matter of Example 3 includes, wherein a periodicity of determining potential collisions is dependent on speed and direction of movement the VR headset.

In Example 5, the subject matter of Examples 3-4 includes, wherein the processor is configured to automatically change the opacity of the darkening layer and deactivate display of the VR image by the display in response to detection of the potential collision.

In Example 6, the subject matter of Examples 3-5 includes, wherein the processor is configured to: control the display to provide a virtual user input in response to detection of the potential collision; and change the opacity of the darkening layer and deactivate display of the VR image by the display in response to user activation of the virtual user input.

In Example 7, the subject matter of Examples 1-6 includes, wherein the darkening layer contains a plurality of segments that each have an individually controllable opacity, and a processor is configured to change the opacity of the segments of the darkening layer from substantially opaque to substantially transparent.

In Example 8, the subject matter of Example 7 includes, a proximity sensor configured to detect a potential collision of the VR headset with an object, wherein the processor is configured to change the opacity of the segments of the darkening layer from substantially opaque to substantially transparent in response to detection of the potential collision.

In Example 9, the subject matter of Example 8 includes, wherein the processor is configured to control the segments of the darkening layer from an outermost segment inward to increase a real world field of view with increasing proximity of the VR headset with the object.

In Example 10, the subject matter of Examples 7-9 includes, a lens disposed more proximate to a viewing point of the VR image than the display to the VR image; and another lens disposed more distal from the viewing point of the VR image than the display to the VR image, the other lens configured to compensate for the lens in response to the darkening layer being substantially transparent.

In Example 11, the subject matter of Example 10 includes, wherein the darkening layer is a layer on the other lens.

In Example 12, the subject matter of Examples 7-11 includes, wherein the processor is configured to determine presence of a particular object within view through image recognition and adjust the opacity of only segments of the darkening layer corresponding to the particular object.

In Example 13, the subject matter of Examples 1-12 includes, a lens disposed more proximate to a viewing point of the VR image than the display to the VR image; and another lens disposed more distal from the viewing point of the VR image than the display to the VR image, the other lens configured to compensate for the lens in response to the darkening layer being substantially transparent.

In Example 14, the subject matter of Examples 1-13 includes, a plurality of lenses disposed more proximate to a viewing point of the VR image than the display to the VR image, each of the lenses having different focal lengths; and a processor configured to at least one of mechanically shift between use of different lenses, adjust a particular lens along a viewing axis, and adjust the particular lens along an axis perpendicular to the viewing axis.

In Example 15, the subject matter of Examples 1-14 includes, a processor configured to: control the display to provide a virtual user input; and change the opacity of the darkening layer and deactivate display of a VR image by the display in response to user activation of the virtual user input.

In Example 16, the subject matter of Examples 1-15 includes, an eye tracker configured to track eye movement of a user eye; and a processor configured to: control the display to provide a virtual user input; determine whether the eye movement tracked by the eye tracker meets a predetermined criteria; and change the opacity of the darkening layer and deactivate display of a VR image by the display in response to a determination that the eye movement meets the predetermined criteria.

In Example 17, the subject matter of Example 16 includes, wherein the predetermined criteria is a movement that is dependent on the VR image.

Example 18 is a layer stack comprising: a substantially transparent display that includes, an array of micro light-emitting diodes (microLEDs) configured to provide a virtual reality (VR) image; and a darkening layer adjacent to the substantially transparent display and having a controllable opacity.

In Example 19, the subject matter of Example 18 includes, wherein the microLEDs are configured to provide light to be viewed on opposing sides of the substantially transparent display, a distance between the microLEDs is configured to provide visibility through the array.

In Example 20, the subject matter of Examples 18-19 includes, wherein the darkening layer contains a plurality of segments that each have an individually controllable opacity.

In Example 21, the subject matter of Example 20 includes, wherein the opacity of the segments of the darkening layer are individually controlled in response to detection of a potential collision with an object.

In Example 22, the subject matter of Example 21 includes, wherein the segments of the darkening layer are controlled from an outermost segment inward with increasing proximity of the object.

In Example 23, the subject matter of Examples 20-22 includes, a lens disposed on a first side of the display and more proximate to the display than to the darkening layer; and another lens disposed on a second side of the display opposite the first side, the other lens configured to compensate for the lens in response to the darkening layer being substantially transparent.

In Example 24, the subject matter of Example 23 includes, wherein the darkening layer is a layer on the other lens.

In Example 25, the subject matter of Examples 20-24 includes, wherein the opacity of only segments of the darkening layer corresponding to a particular object are adjusted in response to presence of the particular object being determined.

In Example 26, the subject matter of Examples 18-25 includes, a lens disposed on a first side of the display and more proximate to the display than to the darkening layer; and another lens disposed on a second side of the display opposite the first side, the other lens configured to compensate for the lens in response to the darkening layer being substantially transparent.

In Example 27, the subject matter of Examples 18-26 includes, a plurality of lenses disposed on a first side of the display, the darkening layer disposed on a second side of the display, each of the lenses having different focal lengths, the lenses configured to be at least one of individually selected and mechanically shift between use of different lenses, adjusted along a viewing axis, and adjusted along an axis perpendicular to the viewing axis.

In Example 28, the subject matter of Examples 18-27 includes, wherein the opacity of the darkening layer is changed, and display of the VR image deactivated in response to user activation of a virtual user input.

In Example 29, the subject matter of Examples 18-28 includes, wherein the opacity of the darkening layer is changed, and display of the VR image deactivated in response to a determination that eye movement meets a predetermined criteria.

In Example 30, the subject matter of Examples 18-29 includes, wherein a distance between the microLEDs in the array is uniform.

Example 31 is a virtual reality (VR) system comprising: a frame configured to receive a head of a user; a substantially transparent display that includes an array of individually-controllable micro light-emitting diodes (microLEDs) con-

figured to provide VR images; a darkening layer having a controllable opacity, the darkening layer disposed between a front of the frame and the substantially transparent display; a processor configured to control the opacity of the darkening layer between an opaque mode in which external light is substantially blocked from passing therethrough and the VR images are provided by the substantially transparent display and a substantially transparent mode in which external light is substantially transmitted therethrough and the VR images are not provided by the substantially transparent display; and a battery configured to provide power to the display, the darkening layer, and the processor.

In Example 32, the subject matter of Example 31 includes, a proximity sensor configured to detect a potential collision of the VR headset with an object, wherein the processor is configured to change the opacity of the darkening layer from substantially opaque to substantially transparent in response to detection of the potential collision.

In Example 33, the subject matter of Example 32 includes, wherein a periodicity of determining potential collisions is dependent on speed and direction of movement the VR headset.

In Example 32, the subject matter of Examples 32-33 includes, wherein the processor is configured to automatically change the opacity of the darkening layer and deactivate display of the VR image by the display in response to detection of the potential collision.

In Example 35, the subject matter of Examples 32-32 includes, wherein the processor is configured to: control the display to provide a virtual user input in response to detection of the potential collision; and change the opacity of the darkening layer and deactivate display of the VR image by the display in response to user activation of the virtual user input.

In Example 36, the subject matter of Examples 31-35 includes, wherein the darkening layer contains a plurality of segments that each have an individually controllable opacity, and a processor is configured to change the opacity of the segments of the darkening layer from substantially opaque to substantially transparent.

In Example 37, the subject matter of Example 36 includes, a proximity sensor configured to detect a potential collision of the VR headset with an object, wherein the processor is configured to change the opacity of the segments of the darkening layer from substantially opaque to substantially transparent in response to detection of the potential collision.

In Example 38, the subject matter of Example 37 includes, wherein the processor is configured to control the segments of the darkening layer from an outermost segment inward to increase a real world field of view with increasing proximity of the VR headset with the object.

In Example 39, the subject matter of Example 38 includes, a lens disposed more proximate to a viewing point of the VR image than the display to the VR image; and another lens disposed more distal from the viewing point of the VR image than the display to the VR image, the other lens configured to compensate for the lens in response to the darkening layer being substantially transparent.

In Example 40, the subject matter of Examples 10-39 includes, wherein the darkening layer is a layer on the other lens.

In Example 41, the subject matter of Examples 38-40 includes, wherein the processor is configured to determine presence of a particular object within view through image recognition and adjust the opacity of only segments of the darkening layer corresponding to the particular object.

In Example 42, the subject matter of Examples 31-41 includes, a lens disposed more proximate to a viewing point of the VR image than the display to the VR image; and another lens disposed more distal from the viewing point of the VR image than the display to the VR image, the other lens configured to compensate for the lens in response to the darkening layer being substantially transparent and the VR headset providing a real world view.

In Example 43, the subject matter of Examples 31-42 includes, a plurality of lenses disposed more proximate to a viewing point of the VR image than the display to the VR image, each of the lenses having different focal lengths, wherein the processor is configured to at least one of mechanically shift between use of different lenses, adjust a particular lens along a viewing axis, and adjust the particular lens along an axis perpendicular to the viewing axis.

In Example 44, the subject matter of Examples 31-43 includes, a processor configured to: control the display to provide a virtual user input; and change the opacity of the darkening layer and deactivate display of a VR image by the display in response to user activation of the virtual user input.

In Example 45, the subject matter of Examples 31-44 includes, an eye tracker configured to track eye movement of a user eye; and a processor configured to: control the display to provide a virtual user input; determine whether the eye movement tracked by the eye tracker meets a predetermined criteria; and change the opacity of the darkening layer and deactivate display of a VR image by the display in response to a determination that the eye movement meets the predetermined criteria.

In Example 45, the subject matter of Example 45 includes, wherein the predetermined criteria is a movement that is dependent on the VR image.

Example 47 is at least one machine-readable medium including instructions that, when executed by processing circuitry, cause the processing circuitry to perform operations to implement of any of Examples 1-46.

Example 48 is an apparatus comprising means to implement of any of Examples 1-46.

Example 49 is a system to implement of any of Examples 1-46.

Example 50 is a method to implement of any of Examples 1-46.

In some embodiments, other components may be present, while in other embodiments not all of the components may be present. As indicated herein, although the term "a" is used herein, one or more of the associated elements may be used in different embodiments. For example, the term "a processor" configured to carry out specific operations includes both a single processor configured to carry out all of the operations as well as multiple processors individually configured to carry out some or all of the operations (which may overlap) such that the combination of processors carry out all of the operations. Further, the term "includes" may be considered to be interpreted as "includes at least" the elements that follow.

While only certain features of the system and method have been illustrated and described herein, many modifications and changes will occur to those skilled in the art. It is, therefore, to be understood that the appended claims are intended to cover all such modifications and changes. Method operations can be performed substantially simultaneously or in a different order.

What is claimed is:

1. A virtual reality (VR) headset comprising:

a frame configured to receive a head of a user;

a substantially transparent display that includes a sparse array of micro light-emitting diodes (microLEDs) configured to display a VR image; and

a darkening layer having a controllable opacity, the darkening layer disposed between a front surface of the frame and the substantially transparent display,

wherein the sparse array of microLEDs includes a rectangular central array of microLEDs surrounded by a peripheral group of microLEDs to mimic a shape of an eye.

2. The VR headset of claim **1**, wherein the microLEDs are configured to provide light to be viewed on opposing sides of the substantially transparent display, and a distance between the microLEDs is configured to provide visibility through the array.

3. The VR headset of claim **1**, further comprising:

a proximity sensor configured to detect a potential collision of the VR headset with an object; and

a processor configured to change the opacity of the darkening layer from substantially opaque to substantially transparent in response to detection of the potential collision.

4. The VR headset of claim **3**, wherein a periodicity of determining potential collisions is dependent on speed and direction of movement the VR headset.

5. The VR headset of claim **3**, wherein the processor is configured to automatically change the opacity of the darkening layer and deactivate display of the VR image by the display in response to detection of the potential collision.

6. The VR headset of claim **3**, wherein the processor is configured to:

control the display to provide a virtual user input in response to detection of the potential collision; and

change the opacity of the darkening layer and deactivate display of the VR image by the display in response to user activation of the virtual user input.

7. The VR headset of claim **1**, wherein the darkening layer contains a plurality of segments that each have an individually controllable opacity, and a processor is configured to change the opacity of the segments of the darkening layer from substantially opaque to substantially transparent.

8. The VR headset of claim **7**, further comprising a proximity sensor configured to detect a potential collision of the VR headset with an object, wherein the processor is configured to change the opacity of the segments of the darkening layer from substantially opaque to substantially transparent in response to detection of the potential collision.

9. The VR headset of claim **8**, wherein the processor is configured to control the segments of the darkening layer from an outermost segment inward to increase a real world field of view with increasing proximity of the VR headset with the object.

10. The VR headset of claim **7**, further comprising:

a lens disposed more proximate to a viewing point of the VR image than the display to the VR image; and

another lens disposed more distal from the viewing point of the VR image than the display to the VR image, the other lens configured to compensate for the lens in response to the darkening layer being substantially transparent.

11. The VR headset of claim **10**, wherein the darkening layer is a layer on the other lens.

12. The VR headset of claim **7**, wherein the processor is configured to determine presence of a particular object within view through image recognition and adjust the opacity of only segments of the darkening layer corresponding to the particular object.

13. The VR headset of claim **1**, further comprising:

a lens disposed more proximate to a viewing point of the VR image than the display to the VR image; and

another lens disposed more distal from the viewing point of the VR image than the display to the VR image, the other lens configured to compensate for the lens in response to the darkening layer being substantially transparent.

14. The VR headset of claim **1**, further comprising:

a plurality of lenses disposed more proximate to a viewing point of the VR image than the display to the VR image, each of the lenses having different focal lengths; and

a processor configured to at least one of mechanically shift between use of different lenses, adjust a particular lens along a viewing axis, and adjust the particular lens along an axis perpendicular to the viewing axis.

15. The VR headset of claim **1**, further comprising a processor configured to:

control the display to provide a virtual user input; and

change the opacity of the darkening layer and deactivate display of a VR image by the display in response to user activation of the virtual user input.

16. The VR headset of claim **1**, further comprising:

an eye tracker configured to track eye movement of a user eye; and

a processor configured to:

control the display to provide a virtual user input;

determine whether the eye movement tracked by the eye tracker meets a predetermined criteria; and

change the opacity of the darkening layer and deactivate display of a VR image by the display in response to a determination that the eye movement meets the predetermined criteria.

17. The VR headset of claim **16**, wherein the predetermined criteria is a movement that is dependent on the VR image.

18. The VR headset of claim **1**, wherein:

the microLEDs include infrared microLEDs configured to emit infrared light to track eye motion and gaze direction, and visible microLEDs configured to emit visible light, and

the infrared emitting microLEDs include a first set of microLEDs configured to provide constant illumination of the eye and a second set of micro LEDs configured to provide modulated illumination of the eye for eye tracking.

19. A layer stack comprising:

a substantially transparent display that includes a sparse array of micro light-emitting diodes (micro LEDs) configured to provide a virtual reality (VR) image; and

a darkening layer adjacent to the substantially transparent display, the darkening layer containing a plurality of segments that each have an individually a controllable opacity, an opacity of the segments of the darkening layer being controllable in response to detection of a potential collision with an object from substantially opaque to substantially transparent from an outermost segment of the plurality of segments inward to increase a real world field of view with increasing proximity to the object, the layer stack configured to be coupled to a frame such that the darkening layer is more proximate to a front surface of the frame than the substantially transparent display,

wherein the sparse array of microLEDs includes a rectangular central array of microLEDs surrounded by a peripheral group of microLEDs to mimic a shape of an eye.

20. The layer stack of claim **19**, wherein the plurality of segments are rings that are individually controlled in response to detection of at least one of a potential collision with an object and presence of a particular object.

21. The layer stack of claim **20**, further comprising:

a lens disposed on a first side of the display and more proximate to the display than to the darkening layer; and

another lens disposed on a second side of the display opposite the first side, the other lens configured to compensate for the lens in response to the darkening layer being substantially transparent.

22. The layer stack of claim **19**, wherein the opacity of the darkening layer is changed, and display of the VR image deactivated in response to at least one of user activation of a virtual user input and detection of eye movement that meets a predetermined criteria.

23. The layer stack of claim **19**, wherein:

the microLEDs include infrared microLEDs configured to emit infrared light to track eye motion and gaze direction, and visible microLEDs configured to emit visible light, and

the infrared emitting microLEDs include a first set of microLEDs configured to provide constant illumination of the eye and a second set of micro LEDs configured to provide modulated illumination of the eye for eye tracking.

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