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(54) APPARATUSES INCORPORATING MICRO-LEDS AND METHODS FOR FABRICATING THE SAME

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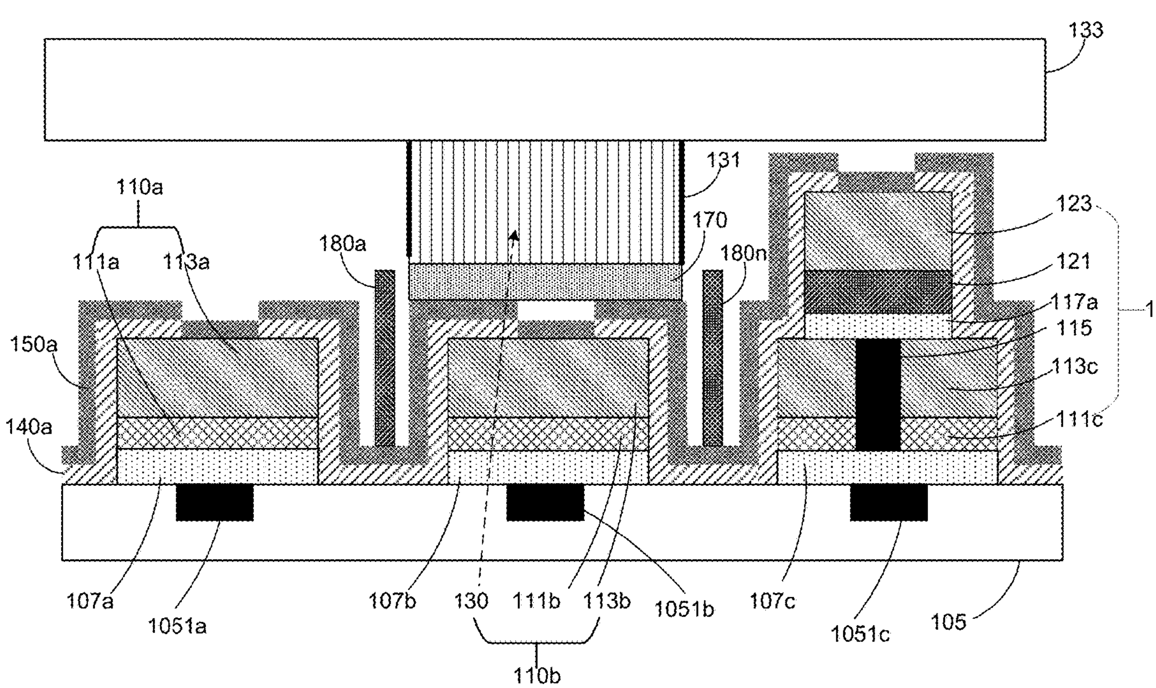
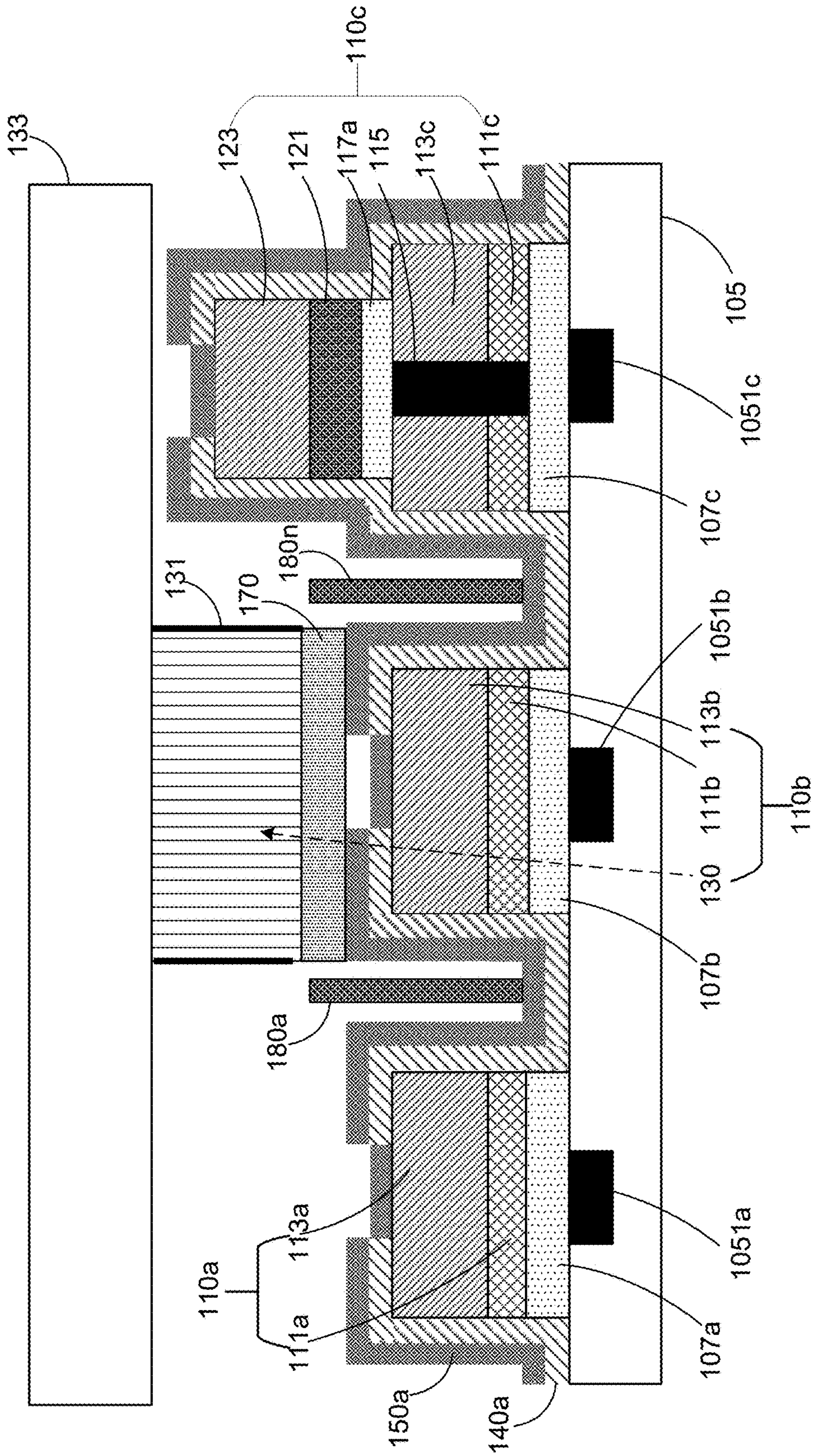
(57) **ABSTRACT**

In accordance with one or more aspects of the present disclosure, an apparatus including pixels is provided. The apparatus may include a first micro light-emitting device configured to emit light of a first color, a second micro light-emitting device configured to emit light of a second color, and a third micro light-emitting device for emitting light of a third color. The first micro light-emitting device includes a first light-emitting structure for emitting light of the first color. The second micro light-emitting device includes a second light-emitting structure for emitting light of the first color. The third micro light-emitting device includes a light-emitting structure for emitting light of the third color that is formed on a third light-emitting structure for emitting light of the first color.

100A



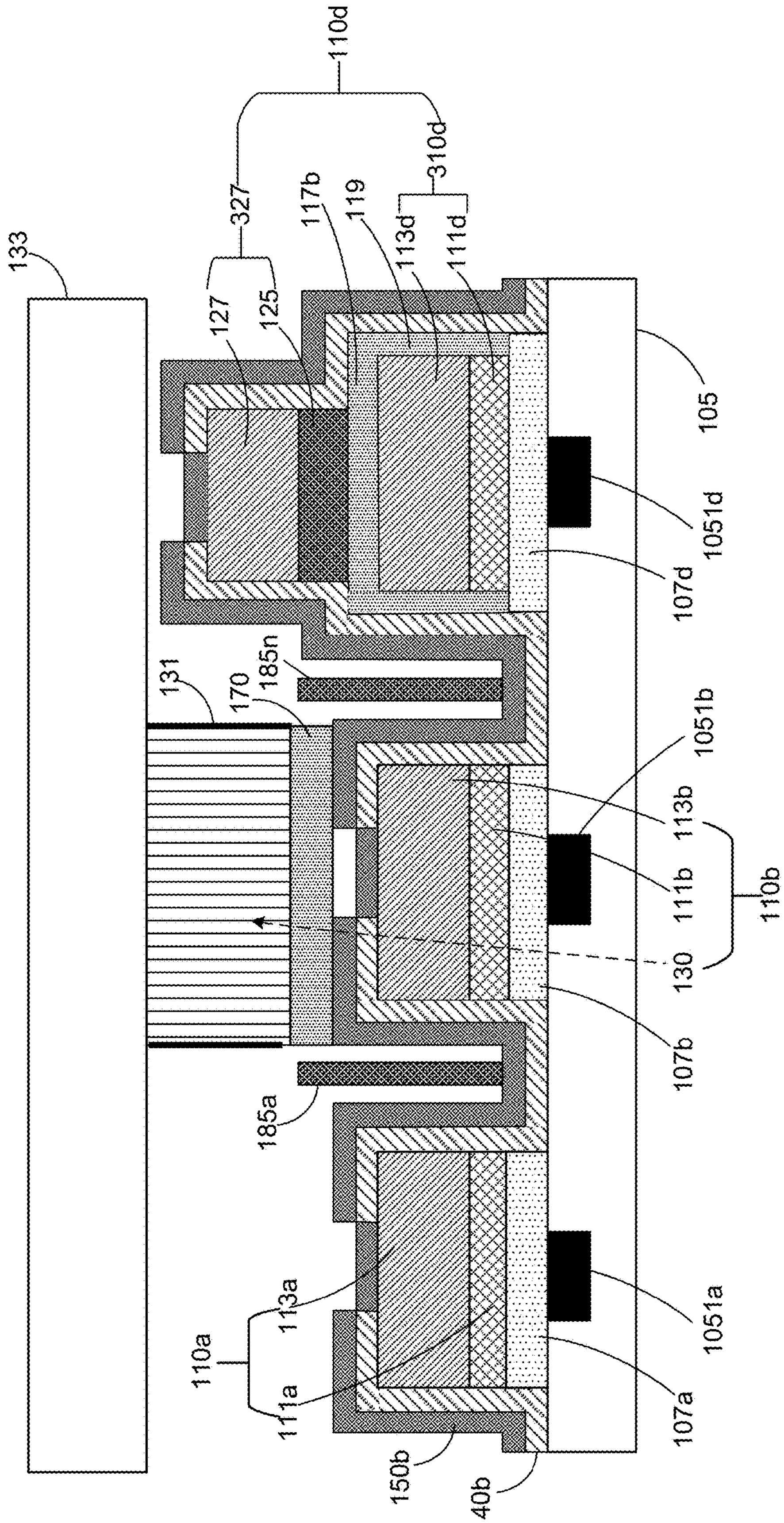
100A



133
110c
123
121
117a
115
113c
111c
105
1051c
107c
180n
131
170
1051b
113b
111b
110b
130
107b
180a
113a
110a
111a
1051a
107a
150a
140a

FIG. 1A

100B



110d
327
310d
117b
119
113d
111d
133
127
125
105
1051d
107d
185n
170
131
1051b
113b
111b
110b
130
107b
185a
1051a
113a
110a
111a
107a
150b
140b

FIG. 1B

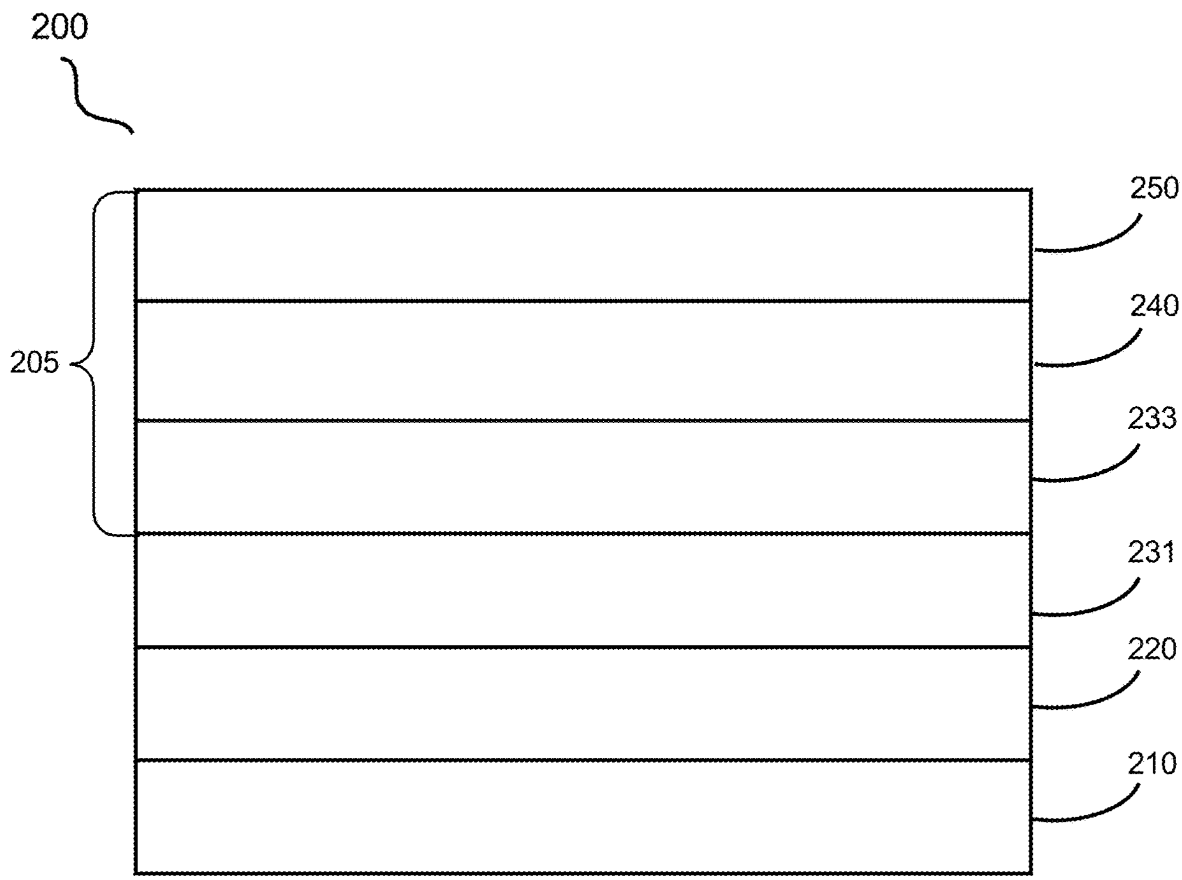


FIG. 2

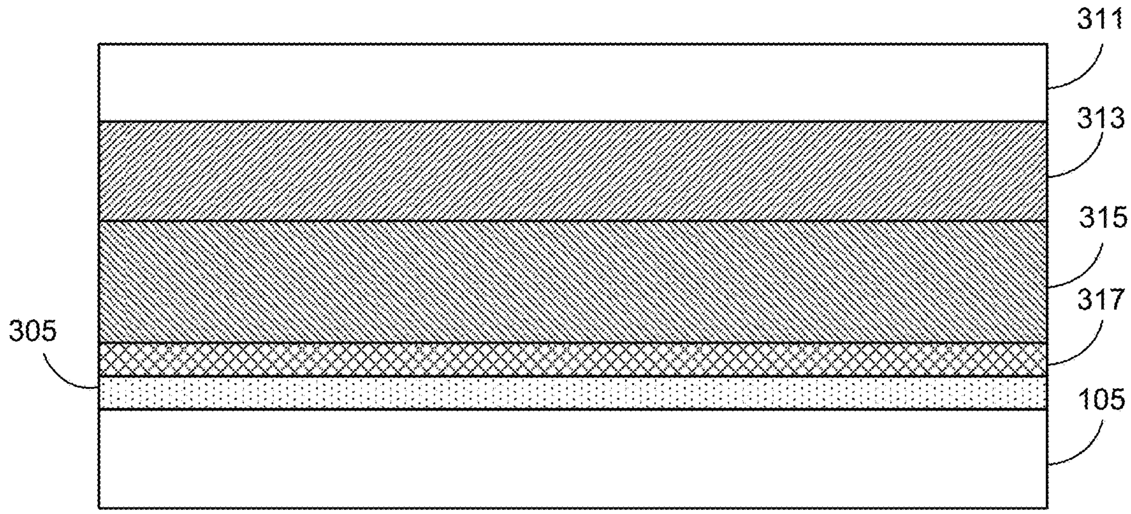


FIG. 3A

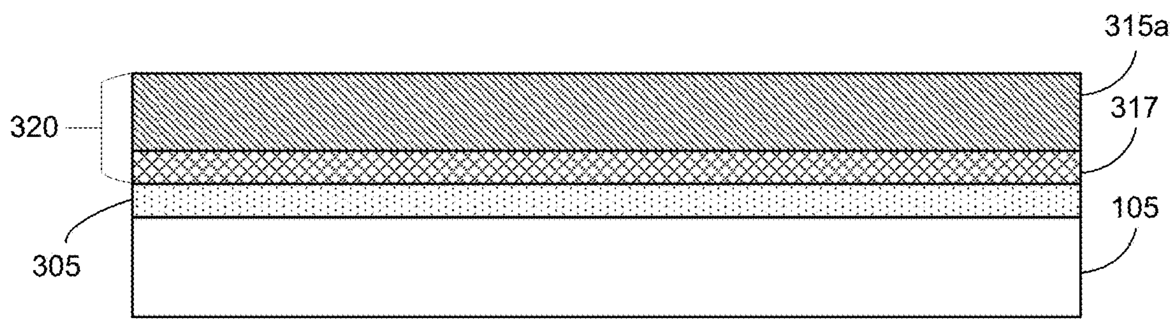


FIG. 3B

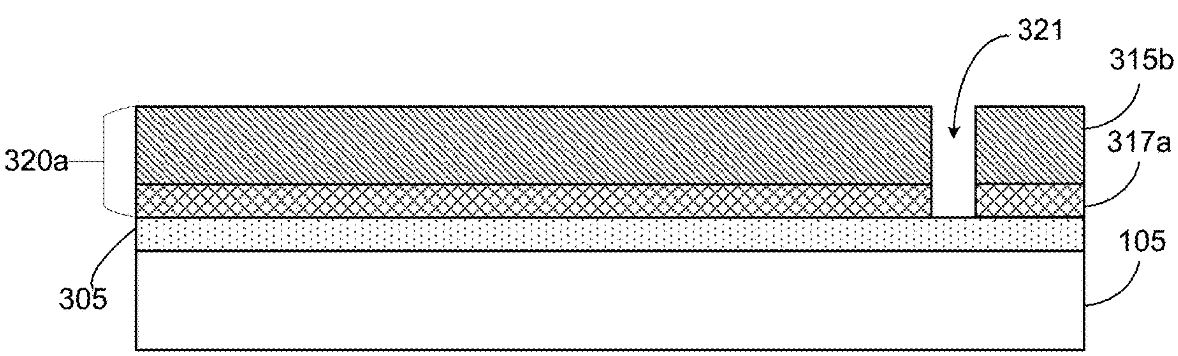


FIG. 3C

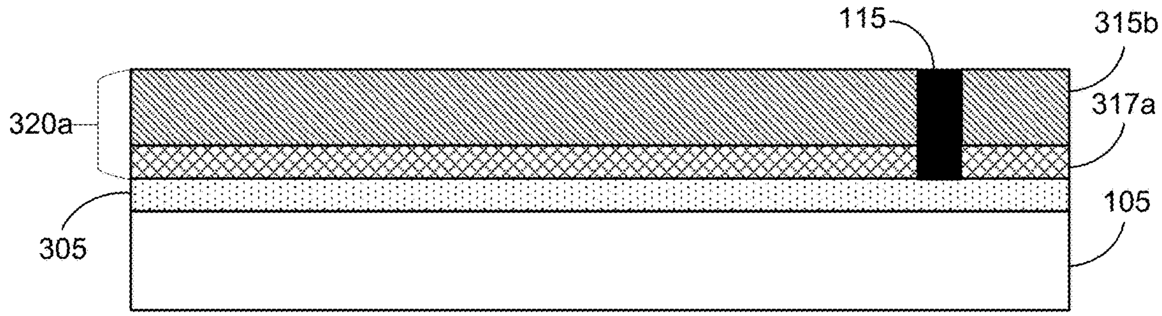


FIG. 3D

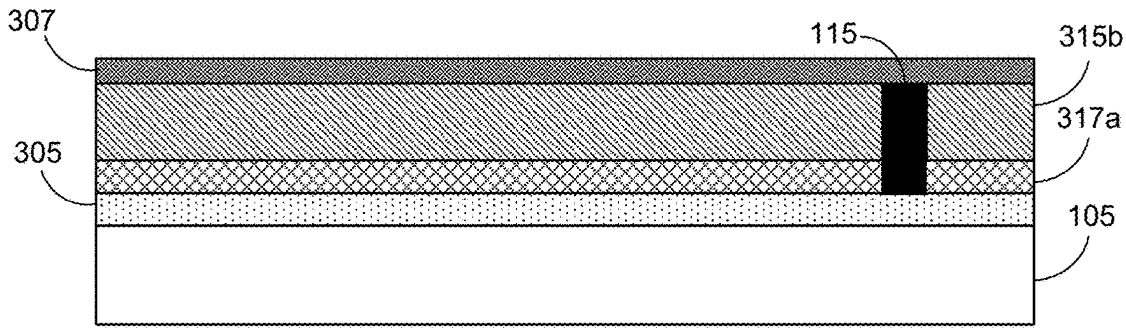


FIG. 3E

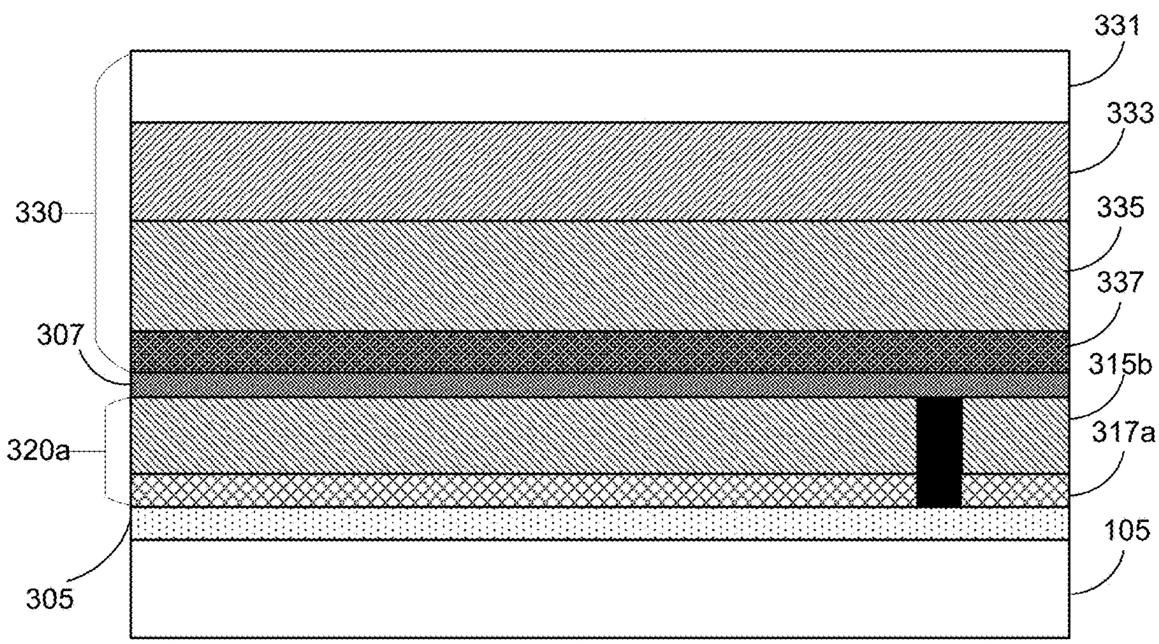


FIG. 3F

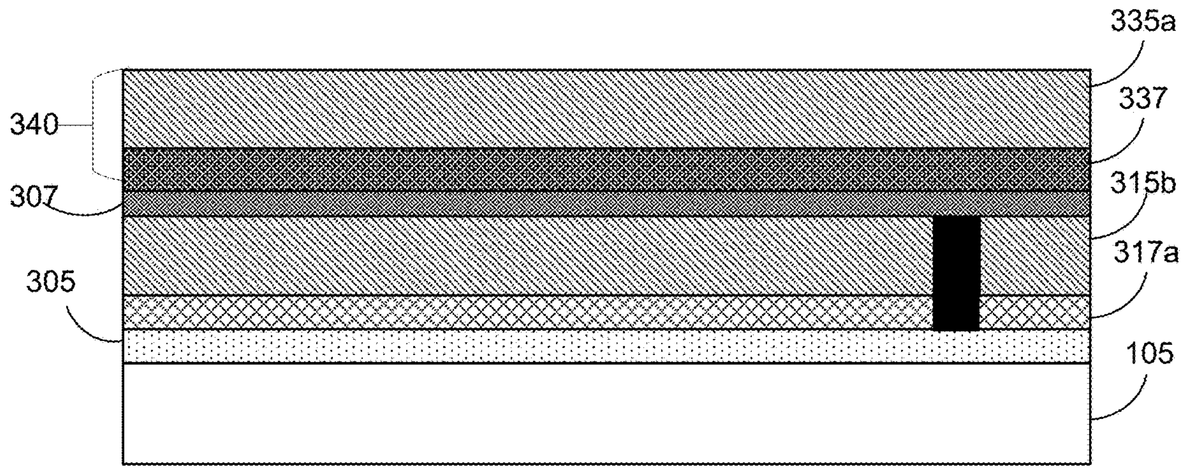


FIG. 3G

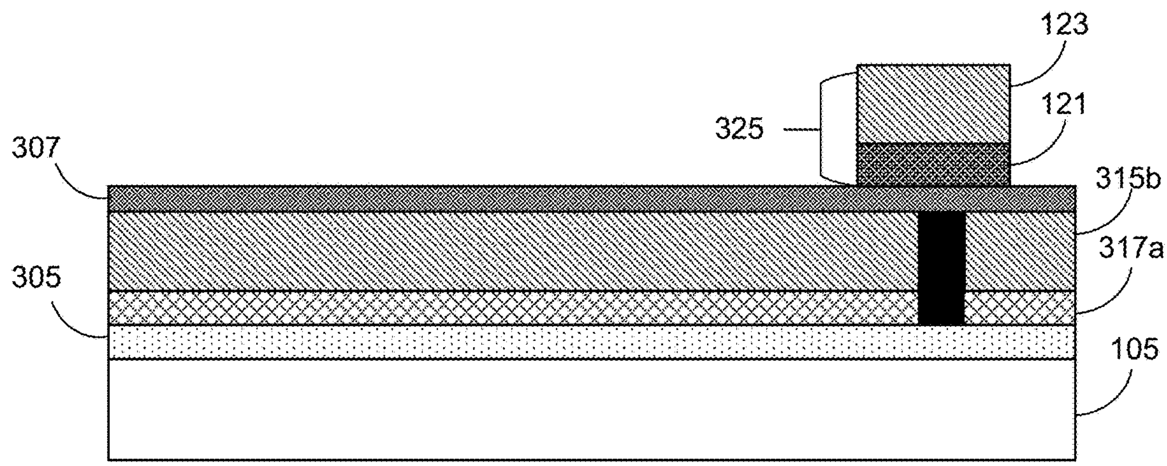


FIG. 3H

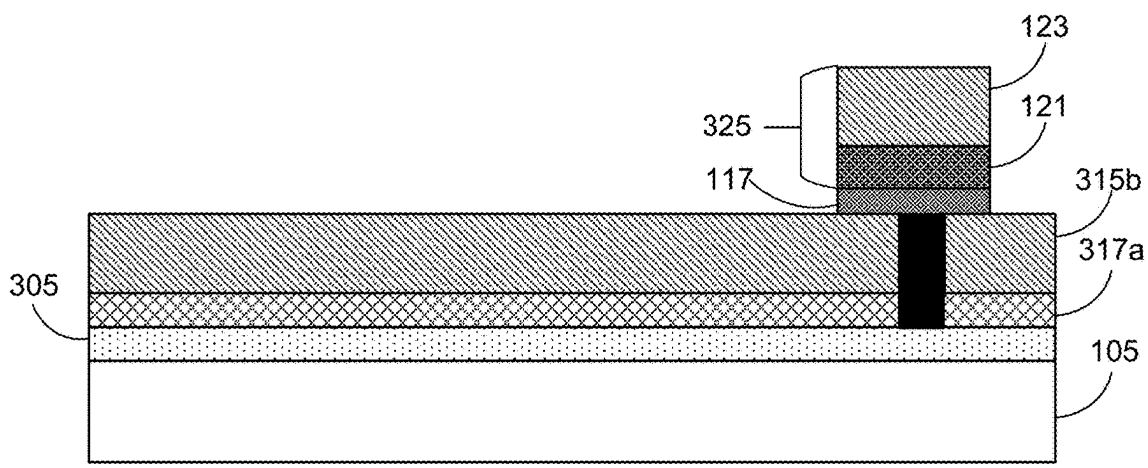


FIG. 3I

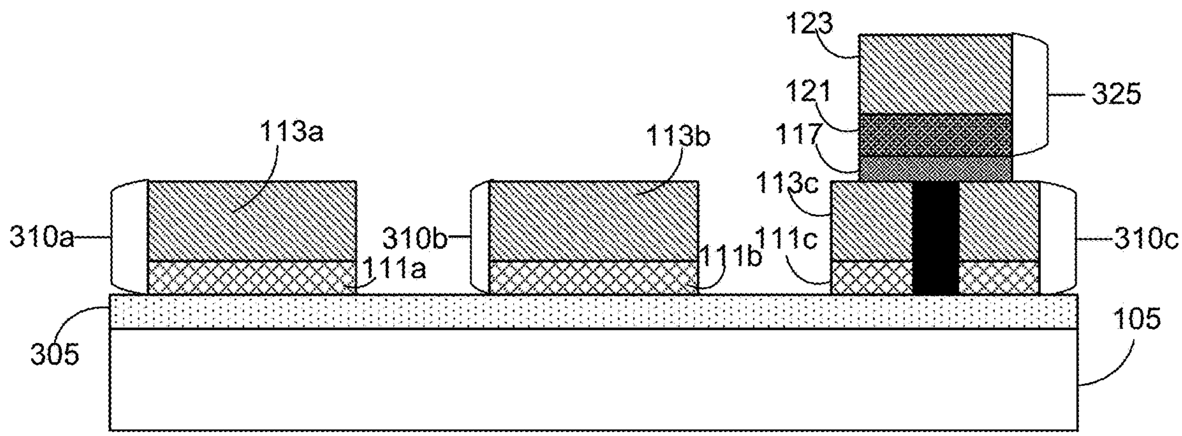


FIG. 3J

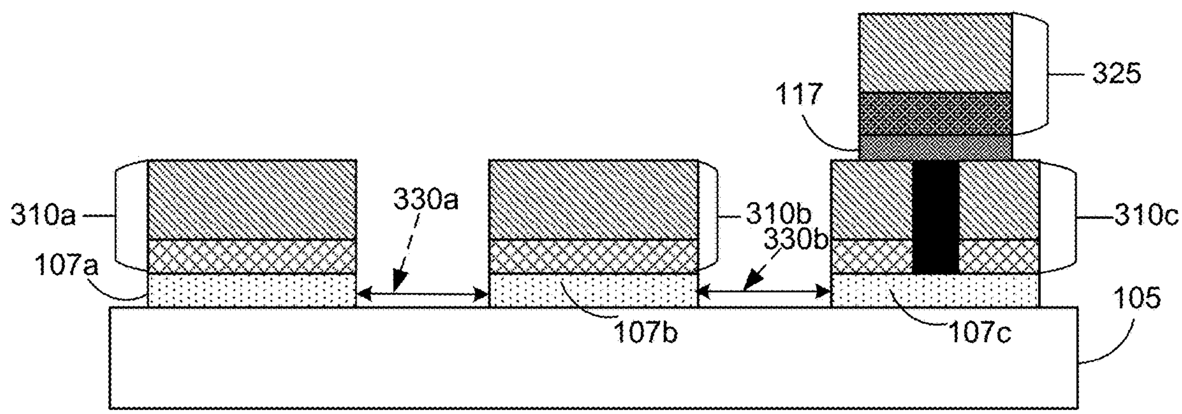


FIG. 3K

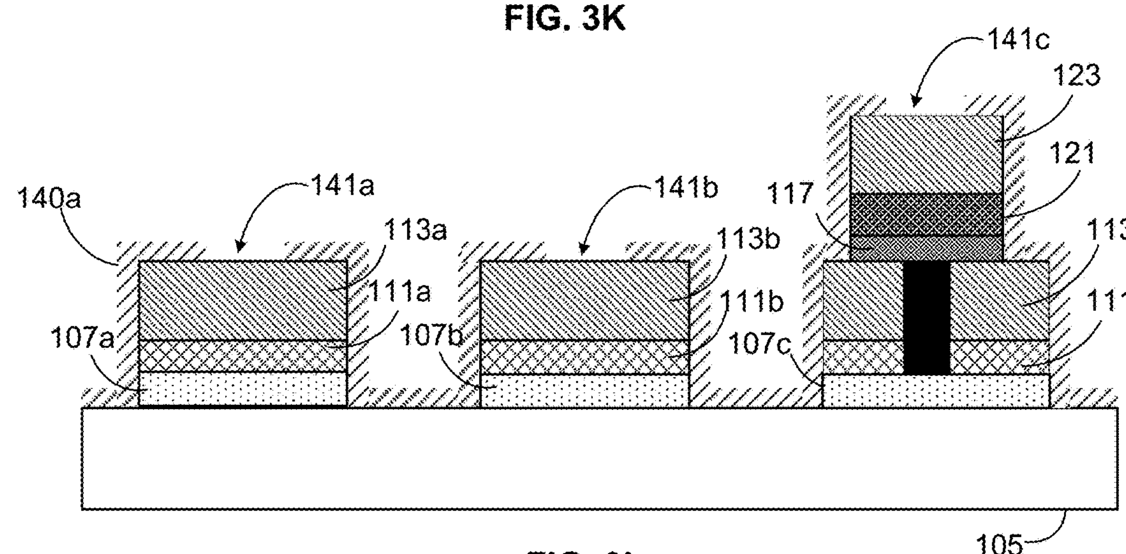


FIG. 3L

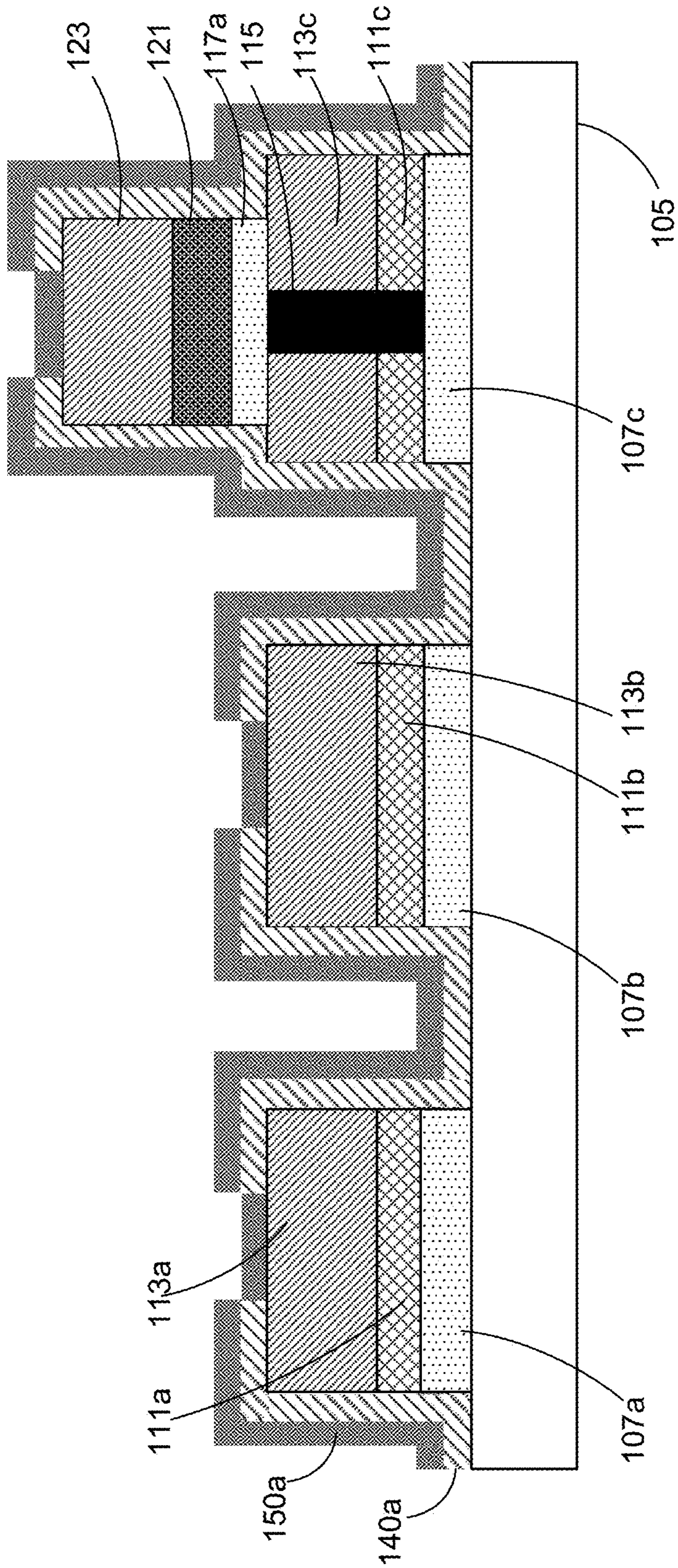

123
121
117a
115
113c
111c
105
107c
113b
111b
107b
113a
111a
107a
150a
140a

FIG. 3M

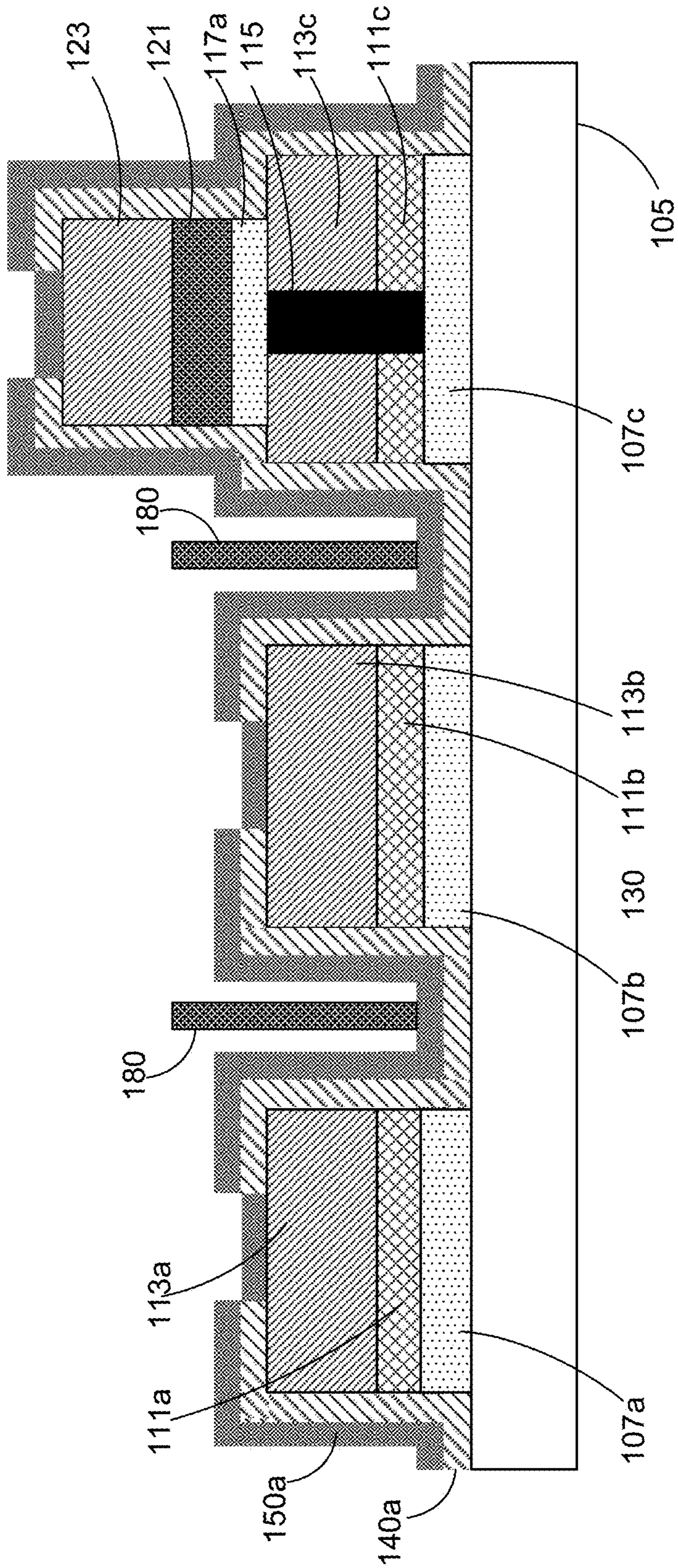

123
121
117a
115
113c
111c
105
107c
180
113b
111b
130
107b
180
113a
111a
107a
150a
140a

FIG. 3N

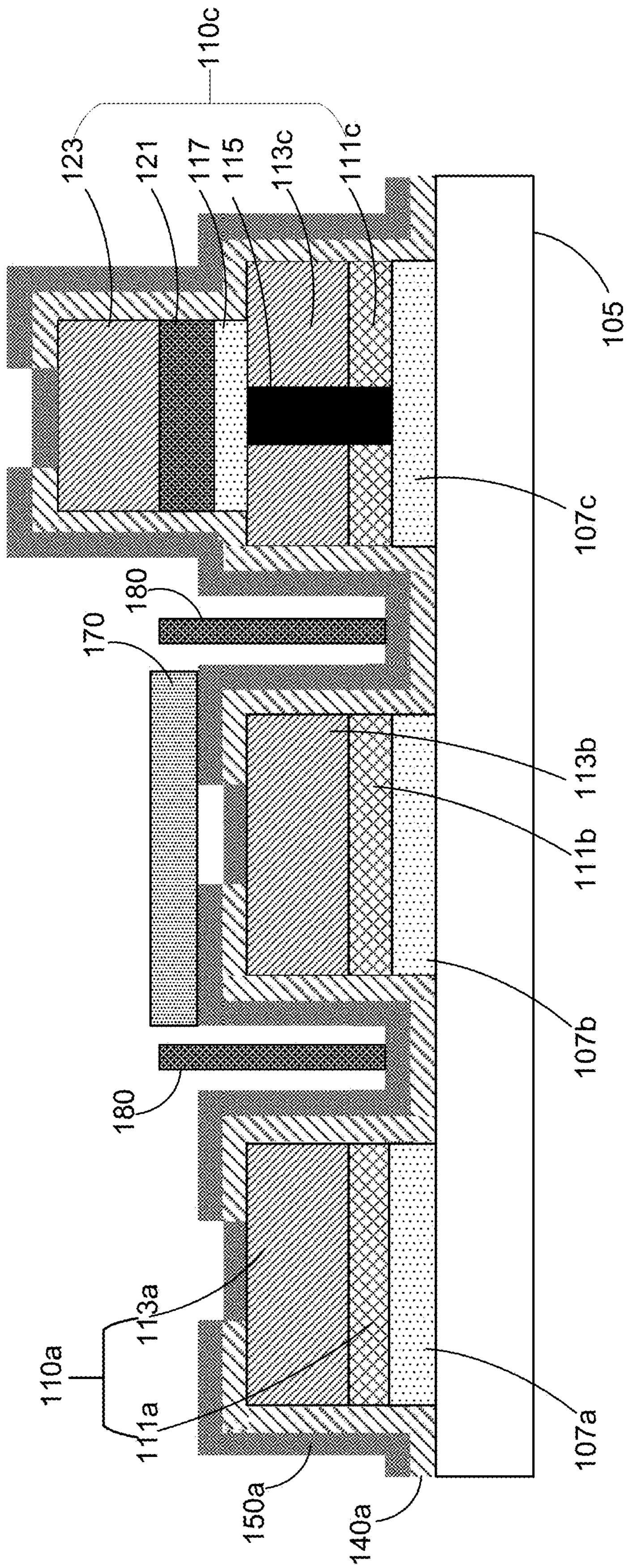

110c
123
121
117
115
113c
111c
105
107c
180
170
113b
111b
107b
180
110a
113a
111a
107a
150a
140a

FIG. 3O

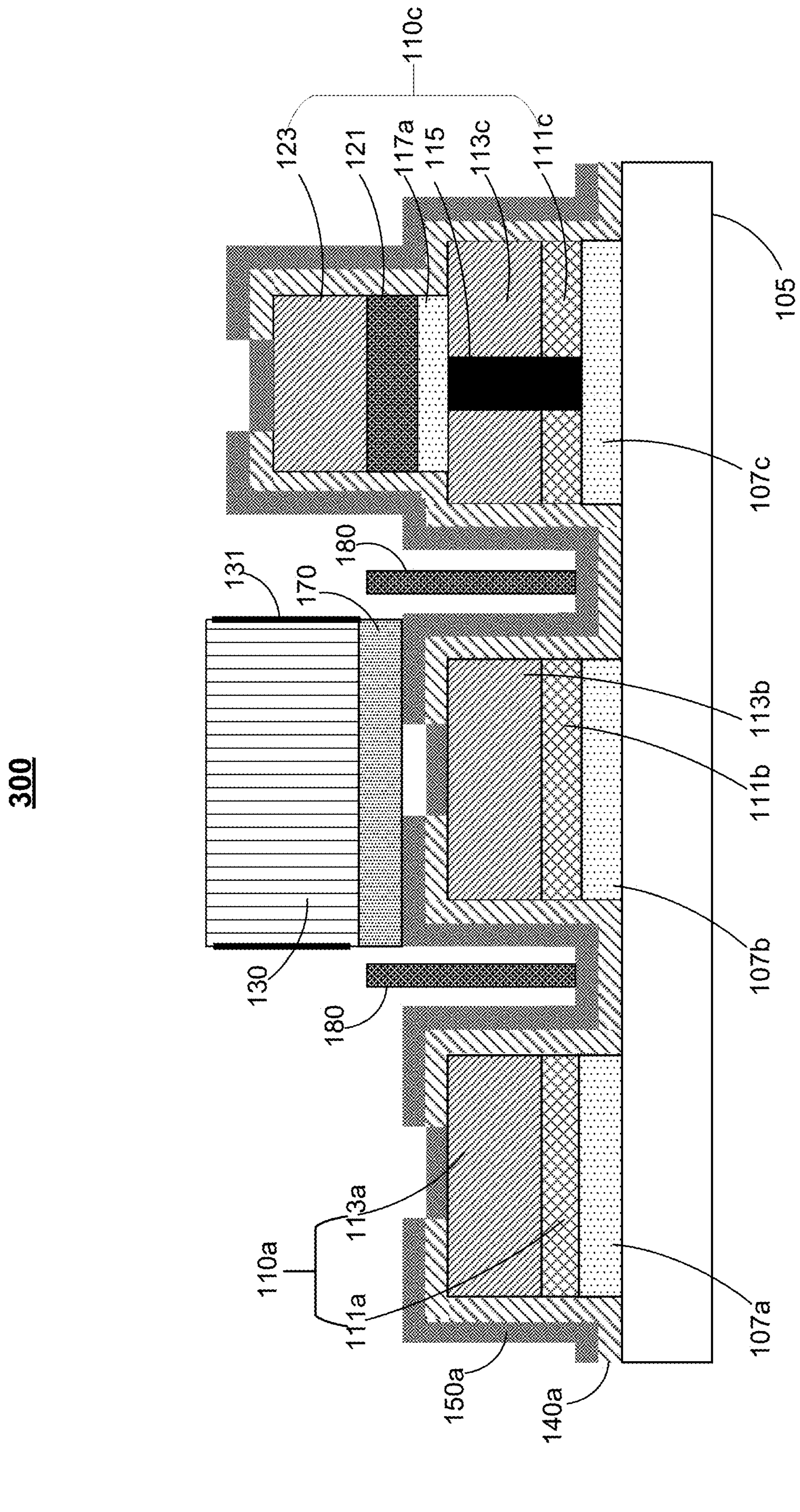

300
110c
123
121
117a
115
113c
111c
105
107c
131
170
180
113b
111b
107b
130
180
110a
113a
111a
107a
150a
140a

FIG. 3P

400

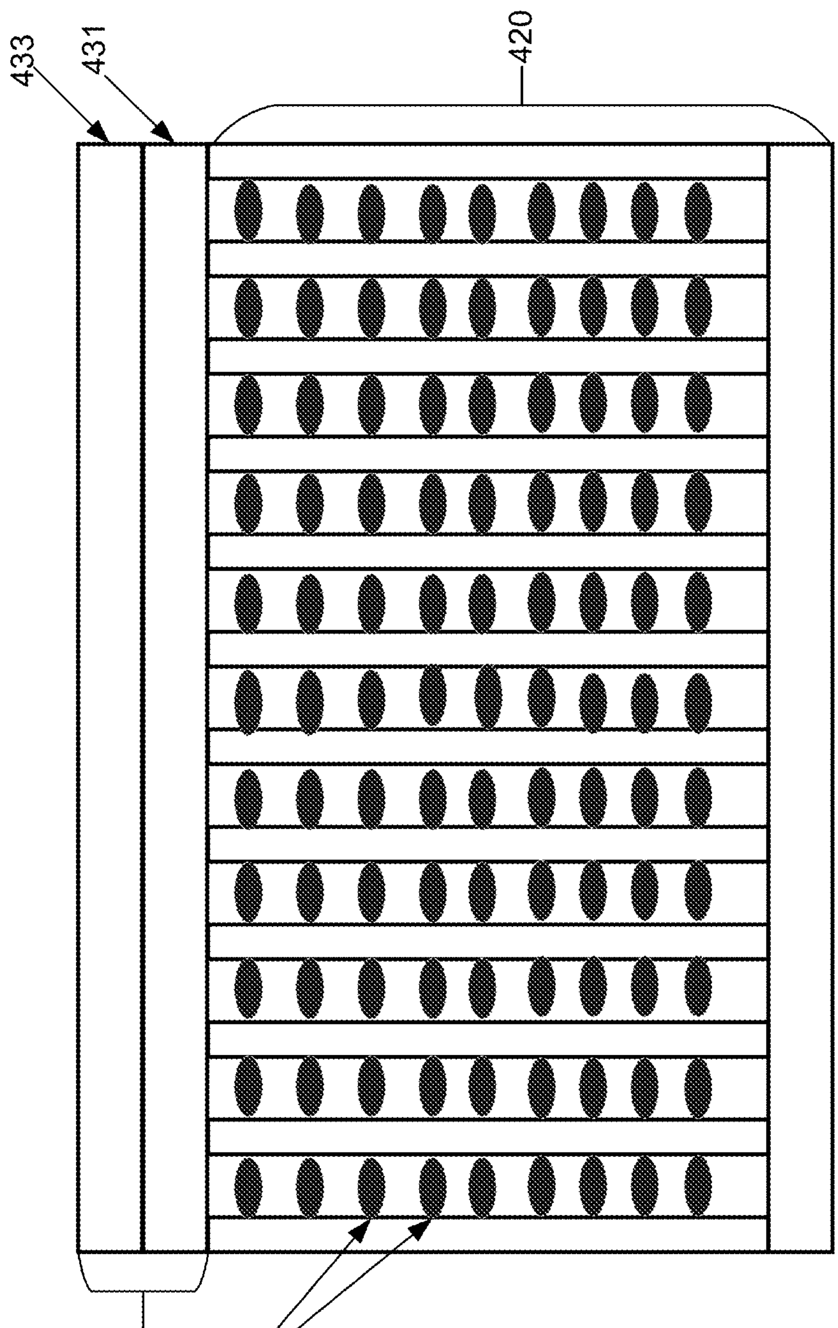


FIG. 4

500

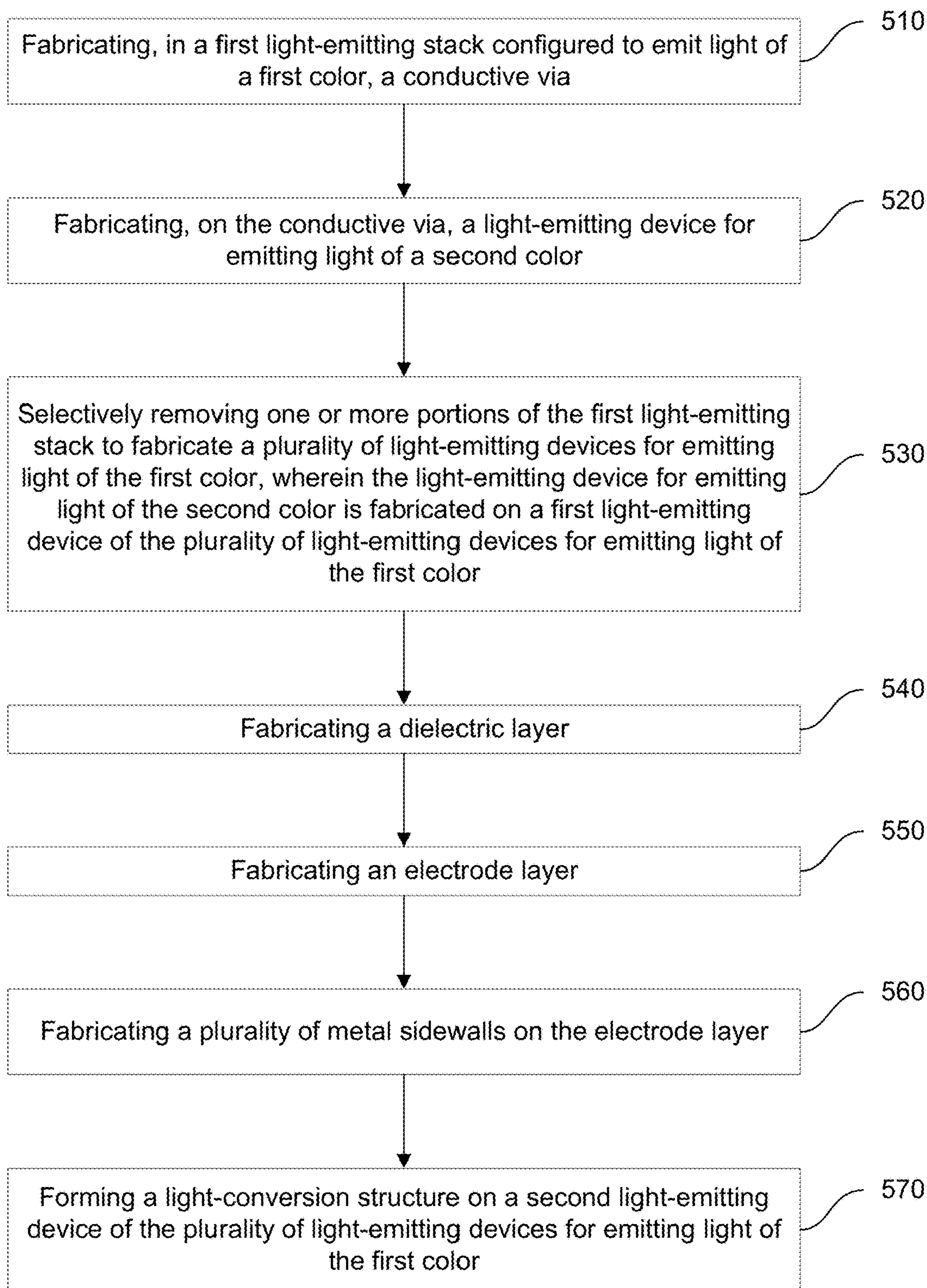

Fabricating, in a first light-emitting stack configured to emit light of a first color, a conductive via
510
Fabricating, on the conductive via, a light-emitting device for emitting light of a second color
520
Selectively removing one or more portions of the first light-emitting stack to fabricate a plurality of light-emitting devices for emitting light of the first color, wherein the light-emitting device for emitting light of the second color is fabricated on a first light-emitting device of the plurality of light-emitting devices for emitting light of the first color
530
Fabricating a dielectric layer
540
Fabricating an electrode layer
550
Fabricating a plurality of metal sidewalls on the electrode layer
560
Forming a light-conversion structure on a second light-emitting device of the plurality of light-emitting devices for emitting light of the first color
570

FIG. 5

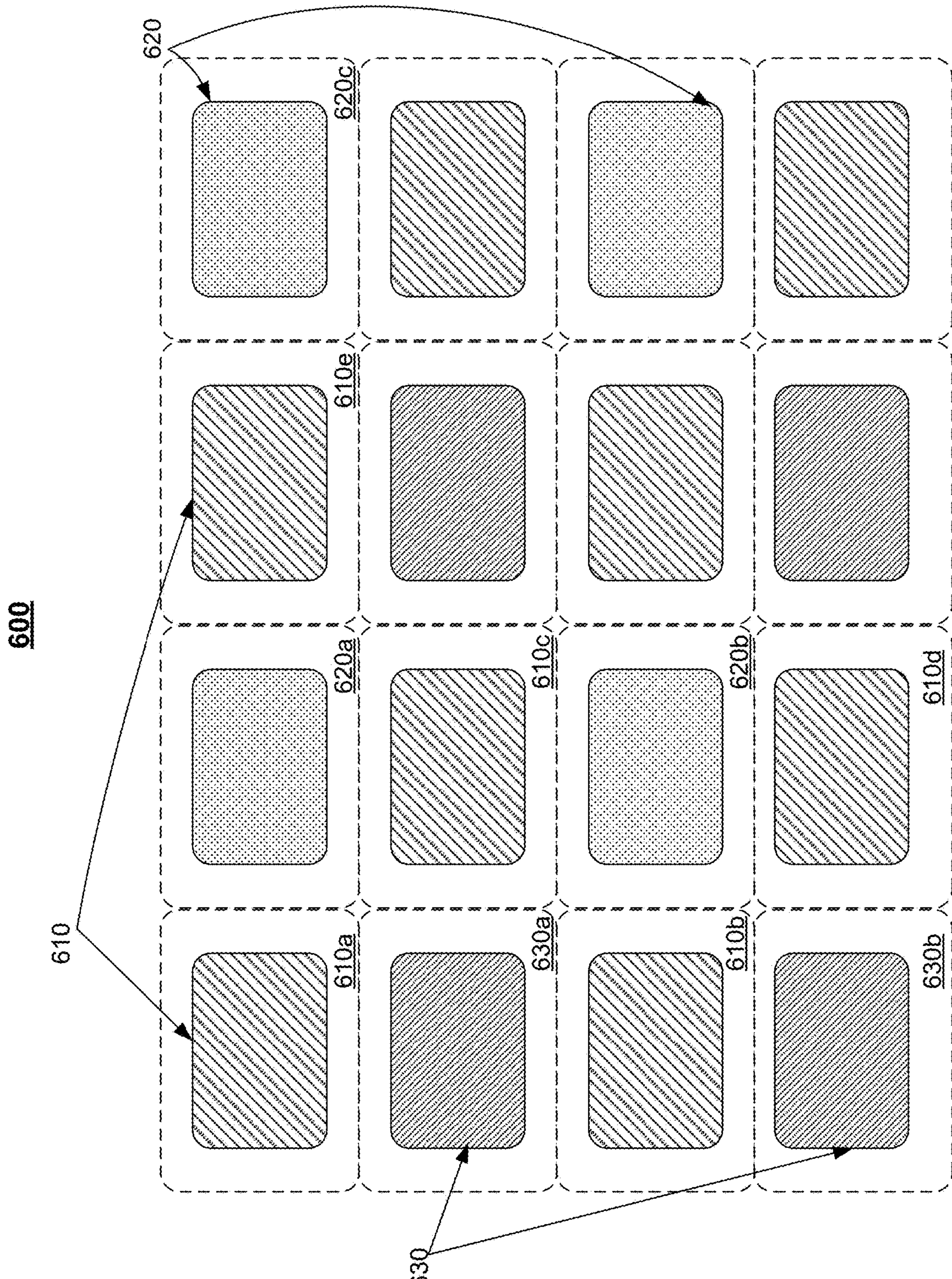

600
610
620
630
620c
610e
620a
610c
620b
610d
610a
630a
610b
630b

FIG. 6

APPARATUSES INCORPORATING MICRO-LEDS AND METHODS FOR FABRICATING THE SAME

TECHNICAL FIELD

[0001] The implementations of the disclosure relate generally to light-emitting devices (LEDs) and, more specifically, to apparatus incorporating micro-LEDs and methods of fabricating the same.

BACKGROUND

[0002] Displays may employ light-emitting diodes to implement red, blue, and green pixels for producing a broad spectrum of colors for high-quality visual output. It might be desirable to integrate micro-LEDs into displays for greater pixel density and improved color accuracy. However, current techniques for display manufacturing encounter significant challenges in creating full-color displays with micro-LEDs, which primarily involves the complexities in manufacturing and precisely integrating these LEDs at a scale that is necessary for complete full-color pixel arrays.

SUMMARY

[0003] The following is a simplified summary of the disclosure in order to provide a basic understanding of some aspects of the disclosure. This summary is not an extensive overview of the disclosure. It is intended to neither identify key or critical elements of the disclosure, nor delineate any scope of the particular implementations of the disclosure or any scope of the claims. Its sole purpose is to present some concepts of the disclosure in a simplified form as a prelude to the more detailed description that is presented later.

[0004] According to one or more aspects of the present disclosure, an apparatus may include a plurality of light-emitting devices for emitting light of a first color and a light-emitting device for emitting light of a second color. The light-emitting device for emitting light of the second color is fabricated on a first light-emitting device of the plurality of light-emitting devices for emitting light of the first color.

[0005] In some embodiments, the light-emitting device for emitting light of the second color is electrically connected to a conductive pad, whereas the first light-emitting device of the plurality of light-emitting devices for emitting light of the first color is bonded to the conductive pad.

[0006] In some embodiments, the light-emitting device for emitting light of the second color is bonded to the first light-emitting device of the plurality of light-emitting devices for emitting light of the first color.

[0007] In some embodiments, the apparatus may further include a conductive via fabricated in the first light-emitting device of the plurality of light-emitting devices for emitting light of the first color.

[0008] In some embodiments, a sidewall of the first light-emitting device of the plurality of light-emitting devices for emitting light of the first color is coated with a conductive material.

[0009] In some embodiments, the light-emitting device for emitting light of the second color is electrically connected to the conductive pad through the conductive material.

[0010] In some embodiments, the apparatus may further include a light-conversion structure that converts light emitted by a second light-emitting device of the plurality of light-emitting devices for emitting light of the first color into light of a third color.

[0011] In some embodiments, the light-conversion structure includes a plurality of quantum dots.

[0012] In some embodiments, the apparatus may further include an electrode layer, wherein the electrode layer is fabricated on the light-emitting device for emitting light of the second color, the second light-emitting device of the plurality of light-emitting devices for emitting light of the first color, and a third light-emitting device of the plurality of light-emitting devices for emitting light of the first color.

[0013] In some embodiments, the apparatus may further include a plurality of metal sidewalls fabricated on the electrode layer.

[0014] In some embodiments, the apparatus may further include a substrate, wherein the plurality of light-emitting devices for emitting light of the first color is bonded to the substrate.

[0015] According to one or more aspects of the present disclosure, a method for fabricating an apparatus incorporating micro-LEDs is provided. The method includes: fabricating, in a first light-emitting stack configured to emit light of a first color, a conductive via; fabricating, on the conductive via, a light-emitting device for emitting light of a second color; selectively removing one or more portions of the first light-emitting stack to fabricate a plurality of light-emitting devices for emitting light of the first color, wherein the light-emitting device for emitting light of the second color is fabricated on a first light-emitting device of the plurality of light-emitting devices for emitting light of the first color.

[0016] In some embodiments, fabricating the conductive via in the first light-emitting stack includes creating an opening in the first light-emitting stack and depositing a metallic material in the opening.

[0017] In some embodiments, the first light-emitting stack is bonded to a substrate prior to fabricating the conductive via.

[0018] In some embodiments, the method further includes fabricating a light-conversion structure on a second light-emitting device of the plurality of light-emitting devices for emitting light of the first color.

[0019] In some embodiments, the light-conversion structure includes a plurality of quantum dots.

[0020] In some embodiments, fabricating, on the conductive via, the light-emitting structure for emitting light of the second color includes: bonding a second light-emitting stack to the first light-emitting stack and the conductive via; and selectively removing one or more portions of the second light-emitting stack to form the light-emitting structure for emitting light of the second color.

[0021] In some embodiments, the method further includes fabricating an electrode layer, wherein the electrode layer provides ohmic contact for the light-emitting device for emitting light of the second color and the second light-emitting device of the plurality of light-emitting devices for emitting light of the first color.

[0022] In some embodiments, forming the light-conversion structure on the second light-emitting structure of the plurality of light-emitting structures for emitting light of the first color includes bonding the light-conversion structure to the electrode layer.

[0023] In some embodiments, the first light-emitting stack includes a plurality of epitaxial layers of a group III-V material.

BRIEF DESCRIPTION OF THE DRAWINGS

[0024] The disclosure will be understood more fully from the detailed description given below and from the accompanying drawings of various embodiments of the disclosure. The drawings, however, should not be taken to limit the disclosure to the specific embodiments, but are for explanation and understanding only.

[0025] FIGS. **1**A and **1**B illustrate cross-sectional views of example apparatuses in accordance with some embodiments of the present disclosure.

[0026] FIG. **2** is a diagram illustrating a cross-sectional view of an example semiconductor device in accordance with some embodiments of the present disclosure.

[0027] FIGS. **3**A, **3**B, **3**C, **3**D, **3**E, **3**F, **3**G, **3**H, **3**I, **3**J, **3**K, **3**L, **3**M, **3**N, **30**, and **3**P are schematic diagrams illustrating cross-sectional views of structures related to a process for fabricating an apparatus incorporating micro-LEDs in accordance with some embodiments of the present disclosure.

[0028] FIG. **4** is a schematic diagram illustrating an example of a light-conversion structure in accordance with some embodiments of the present disclosure.

[0029] FIG. **5** is a flow diagram illustrating an example of a process for fabricating an apparatus incorporating micro-LEDs in accordance with some embodiments of the present disclosure.

[0030] FIG. **6** depicts a schematic diagram illustrating an example pixel arrangement of an example display device in accordance with some embodiments of the present disclosure.

DETAILED DESCRIPTION

[0031] Aspects of the disclosure provide for apparatuses incorporating micro light-emitting devices (LEDs) and methods of fabricating the same.

[0032] In some embodiments, a display may include red pixels, green pixels, and blue pixels arranged in one or more arrays. Each of the red pixels, green pixels, and blue pixels may include one or more micro-LEDs with dimensions on the scale of micrometers. In some embodiments, a blue pixel may include a micro-LED configured to emit blue light. A green pixel may include a micro-LED configured to emit green light that may be bonded to another micro-LED configured to emit blue light. In some implementations, a red pixel may include a micro-LED configured to emit blue light and a light-conversion structure configured to convert blue light into red light. In some embodiments, a red pixel may include a micro-LED configured to emit red light.

[0033] As referred to herein, a micro-LED may have dimensions on the scale of micrometers. In one implementation, a dimension (e.g., a lateral dimension) of a micro-LED may be approximately 5-25 μm. In another implementation, a dimension (e.g., a lateral dimension) of the micro-LED may be greater than 25 μm or smaller than 5 μm. A pixel pitch between two neighboring micro-LED may be 20 μm, 25 μm, or any other suitable value. In some embodiments, the pixel pitch may be equal to or greater than 20 μm. The pixel pitch may represent a distance between the micro-LEDS (e.g., a distance between a center of a first micro-LED and a center of a second micro-LED, a distance between a side of the first micro-LED and a side of the second micro-LED, etc.).

[0034] Examples of embodiments of the present disclosure will be described in more detail with reference to the accompanying drawings. It should be understood that the following embodiments are given by way of illustration only to provide a thorough understanding of the disclosure to those skilled in the art. Therefore, the present disclosure is not limited to the following embodiments and may be embodied in different ways. Further, it should be noted that the drawings are not to precise scale and some of the dimensions, such as width, length, thickness, and the like, can be exaggerated for clarity of description in the drawings. Like components are denoted by like reference numerals throughout the specification.

[0035] FIGS. **1**A and **1**B are diagrams illustrating cross-sectional views of example apparatuses **100**A and **100**B in accordance with some embodiments of the present disclosure. Apparatus **100**A-**100**B may be part of a computing device (e.g., a watch, eyeglasses, contact lenses, a mobile phone, a head-mounted display, a tablet computing device, a laptop, a desktop computer, a television, an augmented reality (AR) device, a virtual reality (VR) device, etc.) and/or a display.

[0036] As shown in FIG. **1**A, apparatus **100**A may include pixels **110***a*, **110***b*, . . . , **110***c* fabricated on a substrate **105**. Substrate **105** may include any suitable component for enabling individual electronic control of the light-emitting devices and/or pixels to be fabricated on substrate **105**. Substrate **105** may include a silicon wafer in some embodiments. Substrate **105** may include one or more driver circuits (e.g., thin-film-transistor (TFT) driver circuits, metal-oxide-semiconductor (CMOS) driver circuits, etc.) that may control the brightness of each LED fabricated on substrate **105**.

[0037] In some embodiments, substrate **105** may be a CMOS wafer including CMOS circuitry, such as one or more CMOS drivers, transistors, interconnects, etc. The pixels may be individually controlled by utilizing the driving circuitry, transistors, interconnects, etc., of the CMOS wafer. An individual pixel may be activated to emit light in response to a voltage applied via an interconnect of the CMOS substrate to the pixel and to an electrode layer **150***a*. A transistor or other suitable switch may provide access control to one or more pixels fabricated on substrate **105**.

[0038] As shown in FIG. **1**A, conductive pads **1051***a*, **1051***b*, . . . , **1051***c* may be fabricated on substrate **105**. Each of conductive pads **1051***a*, **1051***b*, . . . , **1051***c* may include any suitable conductive materials, such as metals, metal nitrides, etc. In some embodiments in which substrate **105** is a CMOS substrate, conductive pads **1051***a*, **1051***b*, . . . , **1051***c* may be interconnects of the CMOS substrate (e.g., metallic pads, metallic vias, etc. separated by dielectric materials).

[0039] Pixels **110***a*, **110***b*, and **110***c* may be configured to emit light of different colors. For example, pixels **110***a*, **110***b*, and **110***c* may be configured to emit light of a first color (e.g., blue light), light of a second color (e.g., green light or red light), and light of a third color (e.g., red light or green light), respectively. A pixel pitch between two neighboring pixels may be 20 μm, 25 μm, or any other suitable value. In some embodiments, the pixel pitch may be equal to or greater than 20 μm. The pixel pitch may represent a distance between the micro-LEDs (e.g., a distance between a center of a first pixel and a center of a second pixel, a distance between a side of the first pixel and a side of the second pixel, etc.). While a certain number of pixels are shown in FIG. **1**A, this is merely illustrative. Any suitable number of pixels may be formed on substrate **105** as described herein to fabricate a display of a suitable size.

[0040] Pixels **110***a*, **110***b*, and **110***c* may be bonded to substrate **105** via bonding layers **107***a*, **107***b*, and **107***c*, respectively. Each bonding layer **107***a*, **107***b*, and **107***c* may include any suitable conductive material that may bond pixels **110***a*, **110***b*, and **110***c* to substrate **105** and provide ohmic contact for the bottom side (e.g., the p-GaN side) of light-emitting structures **111***a*, **111***b*, and **111***c*, such as an Au-Sn alloy, indium, etc. As shown in FIG. **1**A, bonding layers **107***a*, **107***b*, and **107***c* may be fabricated on conductive pads **1051***a*, **1051***a*, and **1051***c*, respectively. Each of bonding layers **107***a*, **107***b*, and **107***c* may directly contact one of conductive pads **1051***a*, **1051***a*, and **1051***c* or establish electrical connections with one of conductive pads **1051***a*, **1051***a*, and **1051***c* via other conductive materials (not shown in FIG. **1**A).

[0041] Pixel **110***a* may include a light-emitting structure **111***a* and a semiconductor layer **113***a*. Pixel **110***b* may include a light-emitting structure **111***b* and a semiconductor layer **113***b*. Pixel **110***c* may include a light-emitting structure **111***c*, a semiconductor layer **113***c*, a conductive via **115**, a bonding layer **117***a*, a light-emitting structure **121**, and a semiconductor layer **123**. As shown, conductive via **115** is fabricated in light-emitting structure **111***c* and semiconductor layer **113***c*. Conductive via **115** may directly contact bonding layer **107***c* or establish an electrical connection to bonding layer **107***c* through other electrically conductive materials. Light-emitting structure **121** and semiconductor layer **123** may be bonded to conductive via **115** and semiconductor layer **113***c* via bonding layer **117***a*. Bonding layer **117***a* may include any suitable conductive material that may bond light-emitting structure **121** to semiconductor layer **113***c* and provide ohmic contact for the bottom side (e.g., the p-GaN side) of light-emitting structure **121**, such as metals, alloys (e.g., an Au-Sn alloy), conductive adhesives, etc.

[0042] Each light-emitting structure **111***a*, **111***b*, **111***c*, and **121** may include light-emitting diodes, laser diodes, and/or any other suitable devices capable of producing and/or emitting light of a certain color. In some embodiments, each light-emitting structure **111***a*, **111***b*, and **111***c* may be configured to emit light of the first color (e.g., blue light). Light-emitting structure **121** may be configured to emit light of the second color (e.g., green light). In some embodiments, each light-emitting structure **111***a*, **111***b*, **111***c*, and **121** may include an n-GaN layer, a p-GaN layer, and an active layer positioned between the n-GaN layer and the p-GaN layer. The active layer may contain quantum well structures for emitting light of a certain color. In some embodiments, each light-emitting structure **111***a*, **111***b*, **111***c*, and **121** may include a light-emitting structure **205** as described in connection with FIG. **2**. Each light-emitting structure **111***a* may include an active layer containing quantum well structures for emitting light of the first color (e.g., blue light). Semiconductor layer **123** may include an active layer containing quantum well structures for emitting light of the second color (e.g., green light). Each semiconductor layer **113***a*, **113***b*, **113***c*, and **123** may include one or more epitaxial layers of a group III-V material (e.g., GaN). In some embodiments, each semiconductor layer **113***a*, **113***b*, **113***c*, and **123** may include an n-GaN layer.

[0043] Apparatus **100**A may include a dielectric layer **140***a* of a dielectric material (e.g., silicon dioxide, silicon nitride, etc.). Dielectric layer **140***a* may be fabricated on the top surfaces of pixels **110***a*-**110***c* (e.g., the top surfaces of semiconductor layers **113***a*, **113***b*, and **123**) and in the trenches separating pixels **110***a*-**110***c*. Dielectric layer **140***a* may also cover the sidewalls of pixels **110***a*-**110***c*. At least a portion of the top surface of each pixel **110***a*-**110***c* (e.g., the top surfaces of semiconductor layers **113***a*, **113***b*, and **123**) is not covered by dielectric layer **140***a*. In some embodiments, dielectric layer **140***a* does not cover the top surfaces of pixels **110***a*-**110***c*.

[0044] Electrode layer **150***a* is fabricated on dielectric layer **140***a* and the top surfaces of pixels **110***a*-**110***c* (e.g., the top surfaces of semiconductor layers **113***a*, **113***b*, and **123**). As dielectric layer **140***a* does not cover at least a portion of the top surfaces of semiconductor layers **113***a*, **113***b*, and **123**, some portions of electrode layer **150***a* directly contact the top surfaces of semiconductor layers **113***a*, **113***b*, and **123**. Electrode layer **150***a* may include any suitable conductive material. In some embodiments, electrode layer **150***a* may include indium tin oxide (ITO) and other suitable materials to implement a transparent conductive electrode for pixels **110***a*-**110***c*. In some embodiments, electrode layer **150***a* may be a continuous and/or substantially continuous layer of the conductive material.

[0045] Light-conversion structure **130** may be configured to convert light of the first color (e.g., light emitted by light-emitting structure **111***b*) into light of the third color (e.g., red light) and may be fabricated on electrode layer **150***a*. In some embodiments, light-conversion structure **130** may include quantum dots with emission wavelengths corresponding to light of the third color. In some embodiments, the sidewall(s) of light-conversion structure **130** may be coated with a reflective material **131**. In some embodiments, the light-conversion structure **130** may include a growth template **133**.

[0046] Growth template **133** may be, for example, a sapphire substrate. In some embodiments, light-conversion structure **130** is bonded to electrode layer **150***a* via a bonding layer **170**. Bonding layer **170** may include glue or any other suitable material that may bond light-conversion structure **130** to electrode layer **150***a*. In some embodiments, growth template **133** of apparatus **100**A may be removed. In some embodiments, growth template **133** does not have to be removed if growth template **133** (e.g., a sapphire substrate) provides suitable light transmittance.

[0047] When a suitable voltage is applied to pixel **110***a*-**110***b* (e.g., by applying the voltage to electrode layer **150***a* and/or conductive pads **1051***a* and **1051***b*), light-emitting structure **111***a*-**111***b* may emit light of the first color. When a suitable voltage is applied to pixel **110***c* (e.g., by applying the voltage to electrode layer **150***a* and/or conductive pad **1051***c*), light-emitting structure **121** may emit light of the second color (e.g., green light). Light-emitting structure **111***c* does not produce light due to a short circuit caused by the presence of conductive via **115**.

[0048] Apparatus **100**A may further include metal sidewalls **180***a*, . . . , **180***n* that may prevent crosstalk between pixels **110***a-c*. Metal sidewalls **180***a*, . . . , **180***n* may include suitable metallic material (e.g., Pt, Au, etc.) deposited on electrode layer **150**. As shown, the height of metal sidewalls

180*a*-**180**n may be higher than the height of pixels **110***a* and **110***b*. Metal sidewalls **180***a*-**180**n may be of any suitable shape. In some embodiments, the cross-section of one or more metal sidewalls **180***a*-**180**n may be a trapezoid.

[0049] Referring to FIG. **1**B, apparatus **100**B may include micro light-emitting devices (pixels) **110***a*, **110***b*, . . . , **110***d* fabricated on substrate **105**. Pixels **110***a*, **110***b*, and **110***d* May be bonded to substrate **105** through bonding layers **107***a*, **107***b*, and **107***d*, respectively. In particular, pixels **110***a*, **110***b*, and **110***d* may be bonded to conductive pads **1051***a*, **1051***b*, . . . , and **1051***d*, respectively. Pixels **110***a*-**110***b*, conductive pads **1051***a*, **1051***b*, . . . , and substrate **105** may be the same as their counterparts in FIG. **1**A. Conductive pad **1051***d* and conductive pads **1051***a-b* may include any suitable conductive material. In some embodiments, conductive pad **1051***d* may be an interconnect of a CMOS substrate.

[0050] Pixel **110***d* may include a light-emitting structure **111***d* for emitting light of the first color, a semiconductor layer **113***d*, a bonding layer **117***b*, a light-emitting structure **125**, and a semiconductor layer **127**. Light-emitting structure **111***d* and semiconductor layer **113***d* may be collectively referred to as a light-emitting device **310***d*. Light-emitting structure **125** and semiconductor layer **127** may be collectively referred to as a light-emitting device **327** and may be bonded to semiconductor layer **113***c* via bonding layer **117***b*. Bonding layer **117***b* may include any suitable conductive material that may bond light-emitting structure **125** to semiconductor layer **113***d* and provide ohmic contact for the bottom side (e.g., the p-GaN side) of light-emitting structure **125**, such as metals, alloys (e.g., an Au-Sn alloy), conductive adhesives, etc.

[0051] The sidewalls of semiconductor layer **113***d* and light-emitting structure **111***d* may be covered by a conductive layer **119** that may directly contact bonding layer **107***d* or establish an electrical connection to bonding layer **107***d* through other electrically conductive materials. Conductive layer **119** may include any suitable conductive material, such as metals, alloys (e.g., an Au-Sn alloy), conductive adhesives, etc. Conductive layer **119** may include one or more layers of the conductive material with uniform thickness or varying thicknesses. Conductive layer **119** may be regarded as a part of bonding layer **117***b* in some embodiments.

[0052] Apparatus **100**B may include a dielectric layer **140***b* of a dielectric material (e.g., silicon dioxide, silicon nitride, etc.). Dielectric layer **140***b* may be fabricated on the top surfaces of pixels **110***a*-**110***d* (e.g., the top surfaces of semiconductor layers **113***a*, **113***b*, and **127**) and in the trenches separating pixels **110***a*-**110***d*. Dielectric layer **140***b* may also cover the sidewalls of pixels **110***a*-**110***d*. At least a portion of the top surface of each pixel **110***a*, **110***b*, . . . , **110***d* (e.g., the top surfaces of semiconductor layers **113***a*, **113***b*, and **127**) is not covered by dielectric layer **140***b*. In some embodiments, dielectric layer **140***a* does not cover the top surfaces of pixels **110***a*, **110***b*, . . . , **110***d*.

[0053] Electrode layer **150***b* is fabricated on dielectric layer **140***b* and the top surfaces of pixels **110***a*-**110***d* (e.g., the top surfaces of semiconductor layers **113***a*, **113***b*, and **127**). As dielectric layer **140***b* does not cover at least a portion of the top surfaces of semiconductor layers **113***a*, **113***b*, and **127**, some portions of electrode layer **150***b* directly contact the top surfaces of semiconductor layers **113***a*, **113***b*, and **127**. Electrode layer **150***b* may include any suitable conductive material. In some embodiments, electrode layer **150***b* may include ITO and other suitable materials to implement a transparent conductive electrode for pixels **110***a*-**110***c*. In some embodiments, electrode layer **150***b* may be a continuous and/or substantially continuous layer of the conductive material.

[0054] When a suitable voltage is applied to pixel **110***a* and **110***b* (e.g., by applying the voltage to electrode layer **150***b* and/or conductive pads **1051***a* and **1051***b*), light-emitting structure **111***a*-**111***b* may emit light of the first color. When a suitable voltage is applied to pixel **110***d* (e.g., by applying the voltage to electrode layer **150***b* and/or conductive pad **1051***d*), light-emitting structure **125** may emit light of the third color (e.g., green light, red light, etc.). Light-emitting structure **111***d* does not produce light because the sidewalls of light-emitting structure **111***d* are covered by conductive layer **119**, causing a short circuit.

[0055] Apparatus **100**B may further include metal sidewalls **185***a*, . . . , **185***n* that may prevent crosstalk between pixels **110***a-c*. Metal sidewalls **185***a*, . . . , **180***n* may include suitable metallic material (e.g., Pt, Au, etc.) deposited on electrode layer **150***b*. As shown, the height of metal sidewalls **185***a*-**185***n* may be higher than the height of pixels **110***a* and **110***b*. Metal sidewalls **185***a*-**185***n* may be of any suitable shape. In some embodiments, the cross-section of one or more metal sidewalls **185***a*-**185***n* may be a trapezoid.

[0056] FIG. **2** is a diagram illustrating a cross-sectional view of an example semiconductor device **200** in accordance with some embodiments of the present disclosure.

[0057] As shown, semiconductor device **200** may include a growth template **210**, a buffer layer **220**, a first semiconductor layer **231** and a second semiconductor layer **233** containing a group III-V material doped with a first type of conductive impurity, an active layer **240**, and a third semiconductor layer **250** containing the group III-V material doped with a second type of conductive impurity. In some embodiments, second semiconductor layer **233**, active layer **240**, and third semiconductor layer **250** may also be referred to as light-emitting structure **205**.

[0058] Growth template **210** may include one or more epitaxial layers of the group III-V material (e.g., gallium nitride (GaN)) to be grown on the growth template **210** and/or a foreign substrate. The foreign substrate may contain any other suitable crystalline material that can be used to grow the group III-V material, such as sapphire, silicon carbide (SiC), silicon (Si), quartz, gallium arsenide (GaAs), aluminum nitride (AlN), etc.

[0059] Buffer layer **220** may include one or more epitaxial layers of the group III-V material (e.g., GaN) that are not doped with any particular conductive type of impurity.

[0060] First semiconductor layer **231** and second semiconductor layer **233** may include one or more epitaxial layers of group III-V materials and any other suitable semiconductor material (e.g., GaN) doped with the first type of conductive impurity. The first type of conductive impurity may be an n-type impurity in some embodiments. For example, each of first semiconductor layer **231** and second semiconductor layer **233** may include an n-GaN layer (e.g., a Si-doped GaN layer, a Ge-doped GaN layer, etc.). In some embodiments, first semiconductor layer **231** and second semiconductor layer **233** may be one epitaxial layer of n-GaN. In some embodiments, first semiconductor layer **231** and second semiconductor layer **233** may be multiple n-GaN layers and may or may not contain the same n-doped GaN.

[0061] Active layer **240** may include one or more layers of semiconductor materials and/or any other suitable material for producing light. For example, active layer **240** may include an active layer comprising one or more quantum well structures for producing light. Each of the quantum well structures may be and/or include a single quantum well structure (SQW) and/or a multi-quantum well (MQW) structure. Each of the quantum well structures may include one or more quantum well layers and barrier layers (not shown in FIG. **2**). The quantum well layers and barrier layers may be alternately stacked on one another. The quantum well layers may include indium (e.g., indium gallium nitride). Each of the quantum well layers may be an undoped layer of indium gallium nitride (InGaN) that is not intentionally doped with impurities.

[0062] Each of the barrier layers may be an undoped layer of the group III-V material that is not intentionally doped with impurities. A pair of a barrier layer (e.g., a GaN layer) and a quantum well layer (e.g., an InGaN layer) may be regarded as being a quantum well structure. Active layer **240** may contain any suitable number of quantum well structures. For example, the number of the quantum well structures (e.g., the number of pairs of InGaN and GaN layers) may be 3, 4, 5, etc. The material composition and/or the layer structures of the quantum well layers may vary to emit different colors of light. For example, the proportion of indium in the InGaN layer is higher for green LEDs compared to blue LEDs. In one implementation, active layer **240** may include suitable quantum well structures for emitting blue light. In another implementation, active layer **240** may include suitable quantum well structures for emitting green light. In yet another implementation, active layer **240** may include suitable quantum well structures for emitting red light.

[0063] Third semiconductor layer **250** may include one or more epitaxial layers of the group III-V material and/or any other suitable material. For example, third semiconductor layer **250** can include an epitaxial layer of the group III-V material doped with a second conductive type impurity that is different from the first conductive type impurity. For example, the second conductive type impurity may be a p-type impurity. In some embodiments, third semiconductor layer **250** may include a GaN layer doped with magnesium.

[0064] When energized, active layer **240** may produce and emit light. For example, when an electrical current passes through active layer **240**, electrons from semiconductor layer **233** (e.g., an n-doped GaN layer) may combine in active layer **240** with holes from third semiconductor layer **250** (e.g., a p-doped GaN layer). The combination of the electrons and the holes may emit light. In some embodiments, the active layer **240** may produce light of a certain color (e.g., light with certain wavelengths).

[0065] While certain layers of semiconductor materials are shown in FIG. **2**, this is merely illustrative. For example, one or more intervening layers may or may not be formed between two semiconductor layers of FIG. **2** (e.g., between semiconductor layer **233** and active layer **240**, between active layer **240** and third semiconductor layer **250**, etc.). In one implementation, a surface of second semiconductor layer **233** may directly contact a surface of active layer **240**. In another implementation, one or more intervening layers (not shown in FIG. **2**) may be formed between second semiconductor layer **233** and active layer **240**. One or more intervening layers (not shown in FIG. **2**) may be formed between first semiconductor layer **231** and buffer layer **220**.

[0066] FIGS. **3**A, **3**B, **3**C, **3**D, **3**E, **3**F, **3**G, **3**H, **3**I, **3**J, **3**K, **3**L, **3**M, **3**N, **30**, and **3**P are schematic diagrams illustrating cross-sectional views of structures related to a process for fabricating an apparatus incorporating micro-LEDs in accordance with some embodiments of the present disclosure.

[0067] As shown in FIG. **3**A, a semiconductor device **310** may be bonded to substrate **105**. Semiconductor device **310** may include a growth template **311**, a buffer layer **313**, a semiconductor layer **315**, and a light-emitting structure **317**. Semiconductor layer **315** May contain one or more epitaxial layers of a group III-V material. In some embodiments, semiconductor layer **315** may include one or more n-GaN layers. Light-emitting structure **317** may include an n-GaN layer, an active layer, and a p-GaN layer. Light-emitting structure **317** may be light-emitting structure **205** of FIG. **2**. Growth template **311**, buffer layer **313**, and semiconductor layer **315** may correspond to growth template **210**, buffer layer **220**, and first semiconductor layer **231** of FIG. **2**, respectively.

[0068] Semiconductor device **310** may be bonded to substrate **105** via a bonding layer **305** (e.g., utilizing a metal bonding or any other suitable bonding process). In some embodiments, a p-GaN layer of light-emitting structure **317** may be bonded to substrate **105** via bonding layer **305**.

[0069] As shown in FIG. **3**B, one or more portions of semiconductor device **310** may be removed to expose a surface of semiconductor layer **315**. For example, growth template **311** and buffer layer **313** may be removed (e.g., utilizing ICP (inductively coupled plasma) etching techniques). Semiconductor layer **315** may be thinned (e.g., using ICP techniques). The thinned first semiconductor layer **315** may be referred to as semiconductor layer **315*a***. Semiconductor layer **315*a*** and light-emitting structure **317** may be collectively referred to as light-emitting stack **320**.

[0070] As shown in FIG. **3**C, one or more portions of light-emitting stack **320** may be removed to expose one or more portions of the top surface of bonding layer **305**. In particular, semiconductor layer **315*a*** and light-emitting structure **317** may be patterned and etched to form an opening **321** in light-emitting stack **320**. In some embodiments, a dimension (e.g., the height) of opening **321** may be about 1 μm. The etched semiconductor layer **315*a*** is referred to as semiconductor layer **315*b***. The etched light-emitting structure **317** may be referred to as light-emitting structure **317*a***. Semiconductor layer **315*b*** and light-emitting structure **317*a*** may be collectively referred to as light-emitting stack **320*a***.

[0071] As shown in FIG. **3**D, one or more suitable conductive materials (e.g., metals) may be deposited in opening **321** to form a conductive via **115** in light-emitting stack **320*a***. In some embodiments, conductive via **115** may be a metal via (e.g., a Cu via).

[0072] As shown in FIG. **3**E, a bonding layer **307** may be fabricated on the top surface of semiconductor layer **315*a*** and conductive via **323**. Bonding layer **307** may include any suitable material that may bond the structures to be formed on semiconductor layer **315*a*** to semiconductor layer **315*a*** and provide ohmic contact. In some embodiments, bonding layer **307** may include a layer of an Au-Sn alloy, indium, etc.

[0073] As shown in FIG. **3**F, a semiconductor device **330** may be bonded to light-emitting stack **320*a*** and conductive via **323** through bonding layer **307**. Semiconductor device

330 may include a growth template **331**, a buffer layer **333**, a semiconductor layer **335**, and a light-emitting structure **337**. Light-emitting structure **337** may include an n-GaN layer, an active layer, and a p-GaN layer. Light-emitting structure **337** may be light-emitting structure **205** of FIG. **2**. Growth template **331**, buffer layer **333**, and semiconductor layer **335** may correspond to growth template **210**, buffer layer **220**, and first semiconductor layer **231** of FIG. **2**, respectively.

[0074] As shown in in FIG. **3**G, growth template **331** and buffer layer **333** may be removed. Semiconductor layer **335** may be thinned. The thinned semiconductor layer **335** may be referred to as semiconductor layer **335***a*. Semiconductor layer **335***a* and light-emitting structure **337** may be collectively referred to as light-emitting stack **340**.

[0075] As shown in FIG. **3**H, one or more portions of light-emitting stack **340** may be selectively removed to fabricate a light-emitting device **325** for emitting light of the second color (e.g., green light). For example, semiconductor layer **335***a* may be patterned and etched to fabricate a semiconductor layer **123**. Light-emitting structure **337** may be patterned and etched to fabricate a light-emitting structure **121**. Light-emitting device **325** may be a micro-LED.

[0076] As shown in FIG. **31**, one or more portions of bonding layer **307** may be selectively removed to form bonding layer **117**. Light-emitting device **325** and light-emitting structure **121** may be bonded to semiconductor layer **315***b* via bonding layer **117**.

[0077] Referring to FIG. **3**J, one or more portions of light-emitting stack **320***a* may be selectively removed to fabricate a plurality of light-emitting devices **310***a*, **310***b*, . . . , **310***c*. Each light-emitting device **310***a*, **310***b*, . . . , **310***c* may be a micro-LED. Semiconductor layer **315***a* may be patterned and etched to form semiconductor layers **113***a*, **113***b*, . . . , **113***c*. The patterning and etching of light-emitting structure **317** may form light-emitting structures **111***a*, **111***b*, . . . , **111***c*. Light-emitting device **325** and light-emitting structure **121** may be bonded to light-emitting device **310***c* via bonding layer **117**.

[0078] As shown in FIG. **3**K, one or more portions of bonding layer **305** may be selectively removed to expose multiple portions of a top surface of substrate **105** and to form bonding layers **107***a*, **107***b*, . . . , **107***c*. Light-emitting structures **111***a*, **111***b*, . . . , **111***c* may be bonded to substrate **105** via bonding layers **107***a*, **107***b*, . . . , **107***c*, respectively. As shown in FIGS. **3**J-**3**K, the selective etching of light-emitting stack **320***a* and bonding layer **305** may create a plurality of trenches **330***a*, . . . , **330***b* that separate bonding layers **107***a*-**107***c* and light-emitting devices **310***a-c*.

[0079] As shown in FIG. **3**L, a dielectric layer **140***a* may be fabricated on light-emitting devices **310***a*, **310***b*, and **325**, and in trenches **320***a*-**320***b*. Dielectric layer **140***a* may include a layer of one or more suitable dielectric materials, such as SiO_2, Si_3N_4, etc. Dielectric layer **140***a* may cover the sidewalls of bonding layers **107***a-c*, light-emitting structure **111***a-c*, semiconductor layers **113***a-c*, bonding layer **117**, light-emitting structure **121**, and semiconductor layer **123**. Dielectric layer **140***a* may be and/or include a layer of a dielectric material (e.g., silicon oxide, silicon nitride, etc.) with openings **141***a*, **141***b*, . . . , **141***c*. Openings **141***a*, **141***b*, . . . , **141***c* may expose at least a portion of the top surfaces of light-emitting devices **310***a*, **310***b*, and **325** (e.g., the top surfaces of semiconductor layers **113***a*, **113***b*, . . . , **123**), respectively.

[0080] As shown in FIG. **3**M, electrode layer **150***a* may be fabricated on dielectric layer **140***a* and the portions of the top surfaces of light-emitting devices **310***a*, **310***b*, and **325** (e.g., the top surfaces of semiconductor layers **113***a*, **113***b*, . . . , **123**) that are not covered by dielectric layer **140***a* (e.g., openings **141***a*, **141***b*, . . . , **141***c*).

[0081] As shown in FIG. **3**N, metal sidewalls **180***a-n* may be fabricated on the portions of electrode layer **150***a* that are deposited in trenches **330***a-b*.

[0082] As shown in FIG. **30**, bonding layer **170** may be fabricated on the portion of electrode layer **150***a* that is formed on semiconductor layers **113***b*. A light-conversion structure **130** may be bonded to the top surface of semiconductor layer **113***b* via bonding layer **170** to form apparatus **100**A as described in connection with FIG. **1**A.

[0083] Referring to FIG. **3**P, light-conversion structure **130** may be bonded to a portion of electrode layer **150***a* that covers light-emitting device **310***b* through bonding layer **170**. Light-conversion structure **130** may include any suitable component for converting light emitted by light-emitting device **310***b* into light of a third color (e.g., red light). For example, light-conversion structure **130** may include quantum dots that may convert the light-emitting by light-emitting device **310***b* into light of the third color. As a more particular example, light-conversion structure **130** may include a light-conversion structure **400** as described in connection with FIG. **4**. As another more particular example, light-conversion structure **130** may include a film containing quantum dots. As another example, light-conversion structure **130** may phosphor materials, photoluminescent materials, etc. that may convert the light-emitting by light-emitting device **310***b* into light of the third color.

[0084] As shown in FIGS. **1**A, **1**B, and **3**P, apparatus **100**A, apparatus **100**B, and apparatus **300** may include a first pixel configured to emit light of a first color (pixel **110***a*), a second pixel configured to emit light of a second color (pixel **110***c* or **110***d*), and a third pixel configured to emit light of a third color (pixel **110***b*). Each apparatus **100**A, apparatus **100**B, and apparatus **300** may include a plurality of light-emitting devices for emitting light of the first color (e.g., light-emitting device **310***a*, **310***b*, **310***c*, **310***d*, etc.) and a light-emitting device for emitting light of the second color (e.g., light-emitting device **325**, light-emitting device **327**, etc.). Each of the plurality of light-emitting devices for emitting light of the first color (e.g., light-emitting device **310***a*, **310***b*, **310***c*, **310***d*, etc.) may be bonded to substrate **105** and a conductive pad (e.g., conductive pads **1051***a*, **1051***b*, **1051***c*, **1051***d*, etc.). The light-emitting device for emitting light of the second color is fabricated on a first light-emitting device (e.g., light-emitting device **310***c* or light-emitting device **310***d*) of the plurality of light-emitting devices for emitting light of the first color. The first light-emitting device of the plurality of light-emitting devices for emitting light of the first color may be bonded to a conductive pad (e.g., conductive pad **1051***c* or **1051***d*). The light-emitting device for emitting light of the second color may be electrically connected to the conductive pad. Each apparatus **100**A, apparatus **100**B, and apparatus **300** may further include a light-conversion structure (e.g., light-conversion structure **130**) that may convert light emitted by a second light-emitting device (e.g., light-emitting device **310***b*) of the plurality of light-emitting devices for emitting light of the first color into light of the third color.

[0085] While a certain number of pixels are fabricated on substrate **105** as described above, this is merely illustrative. The operations described in connection with FIGS. **3**A-**3**P may be performed to fabricate multiple sets of red pixels, green pixels, and blue pixels on substrate **105**.

[0086] FIG. **4** is a schematic diagram illustrating an example **400** of a light-conversion structure in accordance with some embodiments of the present disclosure.

[0087] As shown, light-conversion structure **400** may include quantum dots (QDs) **410** placed in a nanoporous structure **420**. QDs **410** may be and/or include semiconductor particles in nanoscale sizes, such as one or more of ZnS, ZnSe, CdSe, InP, CdS, PbS, InP, InAs, GaAs, GaP, etc. QDs **410** may have emission wavelengths corresponding to light of a certain color (e.g., red light, green light, etc.).

[0088] Nanoporous structure **420** may include nanoporous materials containing pores with a nanoscale size (e.g., a size of the order of 1 nm to 1000 nm or larger. The nanoporous materials may include semiconductor materials (Si, GaN, AlN, etc.), glass, plastic, metal, polymer, etc. In some embodiments, nanoporous structure **420** may be grown on a growth template (not shown in FIG. **4**). For example, nanoporous structure **420** may include porous n-GaN layers growing on a sapphire substrate, a silicon substrate, etc.

[0089] Light-conversion structure **400** may further include a protection structure **430**. The protection structure may include one or more materials (e.g., organic materials, inorganic materials) and may protect the QDs from oxygen, water, moisture, and/or other environmental factors. The protection structure may also prevent chemical degradation of the QDs and may enhance the stability of the light conversion device.

[0090] In some embodiments, protection structure **430** may include a first protection layer **431** that covers the surfaces of the QDs placed in the nanoporous structure. The first protection layer **431** may be and/or include a coating on surfaces of the QDs in the nanoporous structure. As an example, protection layer **431** can be formed by spinning coating or spraying the liquid-phase of the protection layer on the surface of porous structure. The liquid-phase protection layer can then flow inside the nanoporous structure. The coating may include one or more suitable materials that may prevent oxidation of the QDs and/or protect the QDs from other environmental factors, such as polydimethylsiloxane (PDMS), poly (methylmethacrylate) (PMMA), epoxy, etc. In some embodiments, as shown in FIG. **4**, protection layer **431** may also include a layer of the first material formed on the nanoporous structure. It is to be noted that the coating that covers the QDs is not shown in FIG. **4**.

[0091] Protection structure **430** may further include a protection layer **433** (also referred to as the "second protection layer"). The protection layer **433** may include one or more materials that may protect the QDs from oxygen, moisture, and/or other environmental factors. For example, protection layer **433** may include one or more layers of SiO_2, SiN, Al_2O_3, PDMS, PMMA, etc. Protection layer **433** may be formed on protection layer **431** to provide further protection for the QDs in the light-conversion structure. The protection layers **431** and **433** may or may not contain the same material.

[0092] In one implementation, protection layer **431** and/or the coating of the QDs include a first material. Protection layer **433** includes a second material that is different from the first material. Examples of the first material may include PDMS, PMMA, epoxy, etc. Examples of the second material may include SiO_2, SiN, Al_2O_3, etc. In another implementation, protection layers **431** and **433** and/or the coating of the QDs may include a common material.

[0093] FIG. **5** is a flow diagram illustrating an example **500** of a process for fabricating an apparatus incorporating pixels in accordance with some embodiments of the present disclosure.

[0094] At **510**, a conductive via may be fabricated in a first light-emitting stack. The first light-emitting stack may include any suitable components for emitting light of a first color (e.g., blue light). For example, the first light-emitting stack may include a plurality of epitaxial layers of a group III-V material (e.g., GaN) and an active layer including quantum well structures for emitting light of the first color. In some embodiments, the first light-emitting stack may be light-emitting stack **320** of FIG. **3**B and may include semiconductor layer **315***a* and light-emitting structure **317**. In some embodiments, the first light-emitting stack may be bonded to a substrate as described in connection with FIGS. **3**A-**3**B above.

[0095] Fabricating the conductive via may involve creating an opening (e.g., opening **321** of FIG. **3**C) in the first light-emitting stack. A metallic material may then be deposited in the opening. In some embodiments, a layer of the metallic material that is thicker than the depth of the opening may be deposited to fill the opening, and the extra metallic material deposited on the first light-emitting stack may be removed (e.g., using chemical mechanical planarization processes).

[0096] At **520**, a light-emitting device for emitting light of a second color may be fabricated on the conductive via and the first light-emitting stack. For example, a second light-emitting stack (e.g., light-emitting stack **340** of FIG. **3**G) may be bonded to the first light-emitting stack and the conductive via through a bonding layer containing conductive bonding materials (e.g., Au, Sn, In, Ag, Ti, Pt, Ni, Al, etc.). The second light-emitting stack may be bonded to the first light-emitting stack and the conductive via using metallic bonding techniques. The second light-emitting stack may include suitable structures for emitting light of the second color. One or more portions of the second light-emitting stack may be selectively removed to form the light-emitting device for emitting light of the second color. For example, the second light-emitting stack may be patterned and etched using photolithography and ICP etching techniques. The light-emitting device for emitting light of the second color may be, for example, light-emitting device **325** of FIG. **3**H and may be fabricated by performing operations as described in connection with FIGS. **3**E-**3**I above.

[0097] At **530**, a plurality of light-emitting devices may be fabricated by selectively removing one or more portions of the first light-emitting stack. For example, the first light-emitting stack may be patterned and etched (e.g., using photolithography and ICP etching techniques) to form light-emitting structures (e.g., the light-emitting structures **111***a*, **111***b*, . . . ,**111***c* of FIG. **3**J) for emitting light of the first color. The light-emitting device for emitting light of the second color (e.g., light-emitting device **325** of FIG. **3**J) is fabricated on a first light-emitting device of the plurality of light-emitting devices for emitting light of the first color (e.g., light-emitting device **310***c* of FIG. **3**J).

[0098] At **540**, a dielectric layer may be fabricated. For example, one or more dielectric materials may be deposited in the trenches that separate the plurality of light-emitting devices for emitting the first color. The dielectric layer may be the dielectric layer **140***a* as described in connection with FIG. **3**L above.

[0099] At **550**, an electrode layer may be fabricated on the dielectric layer. Fabricating the electrode layer may involve depositing a layer of ITO or any other suitable conductive material. The electrode layer may be the electrode layer **150***a* of FIG. **1**A and may be fabricated as described in connection with FIG. **3**M.

[0100] At **560**, a plurality of metal sidewalls may be fabricated. For example, metal sidewalls **180** may be fabricated on the portions of electrode layer **150***a* that are deposited in trenches **330***a-b* as described in connection with FIG. **3**N.

[0101] At **570**, a light-conversion structure may be fabricated on a second light-emitting device of the plurality of light-emitting devices for emitting light of the first color. The light-conversion structure may convert light of the first color into light of a third color (e.g., converting blue light into red light). In one implementation, the light-conversion structure may be bonded to the second light-emitting structure for emitting light of the first color (e.g., by performing operations as described in connection with FIGS. **30**, **1**, and/or **3**P). In another implementation, the light-conversion structure may be formed by fabricating the nanoporous structure on the second light-emitting structure and placing the quantum dots in the nanoporous structure.

[0102] FIG. **6** depicts a schematic diagram illustrating an example pixel arrangement of an example display device **600** in accordance with some embodiments of the present disclosure. Display device **600** may be incorporated into any suitable computing device, such as mobile phones, laptops, desktops, tablet computer devices, wearable computing devices (e.g., watches, eyeglasses, head-mounted displays, virtual reality headsets, activity trackers, clothing, contact lenses, etc.), televisions, etc. Display device **600** may be of any suitable size. Display device **600** may include one or more apparatuses **100**A and/or **100**B as described in connection with FIGS. **1**A-**1**B above.

[0103] As illustrated, display device **600** may include an array of red pixels **610**, green pixels **620**, and blue pixels **630**. The array may contain any suitable number of red pixels, green pixels, and blue pixels to implement a display of a desirable size and/or resolution. In the array, red pixels **610**, green pixels **620**, and blue pixels **630** are arranged such that along a first direction of the array, each row contains either a combination of red pixels and blue pixels or a combination of red pixels and green pixels. None of the rows of the array contain combinations of all three types of pixels (i.e., red pixel, blue pixels, and green pixels). Similarly, in a second direction, each column of the array includes either a combination of red pixels and green pixels or a combination of red pixels and blue pixels. None of the columns of the array contain combinations of all three types of pixels (i.e., red pixel, blue pixels, and green pixels). For example, red pixels **610***a*-**610***c* and blue pixels **630***a*-**630***b* may be arranged in the first column of the array. The first column of the array does not include any green pixel. As another example, the second column of the array may include red pixels **610***c*-**610***d* and green pixels **620***a*-**620***b*, but does not include any blue pixels. The first row of the array includes red pixels **610***a*-**610***e* and green pixels **620***a*-**620***c*, but does not include any blue pixels. The arrangement of the red pixels, the green pixels, and the blue pixels may prevent and/or eliminate optical crosstalk between pixels of different colors.

[0104] Each of red pixels **610**, blue pixels **620**, and green pixels **630** may include a pixel as described in connection with FIGS. **1**A-**1**B. As an example, each blue pixel **620** may include a pixel **110***a* of FIGS. **1**A-**1**B. In one implementation, one or more red pixels **610** may include a light-emitting structure for emitting blue light and a light-conversion structure for converting blue light into red light. For example, one or more red pixels **610** may include pixel **110***b* of FIGS. **1**A-**1**B. In another implementation, one or more red pixels **610** may include a light-emitting structure for emitting red light (e.g., an AlGaInP red micro-LED). The light-emitting structure for emitting red light may be fabricated on a light-emitting structure for emitting blue light (e.g., by bonding the light-emitting structure for emitting red light to the light-emitting structure for emitting blue light).

[0105] One or more green pixels **630** may include a light-emitting structure for emitting green light. The light-emitting structure for emitting green light may be fabricated on a light-emitting structure for emitting blue light. The light-emitting structure for emitting green light may be bonded to the light-emitting structure through suitable bonding materials that are electrically conductive. When a suitable voltage is applied to the green pixel **630**, the light-emitting structure for emitting blue light does not emit light due to a short circuit, and the light-emitting structure for emitting green light may emit green light. For example, one or more green pixels **630** may include pixel **110***c* of FIG. **1**A and/or pixel **110***d* of FIG. **1**B.

[0106] In some embodiments, red pixels **610**, blue pixels **620**, and green pixels **630** may be fabricated utilizing the methods described above in connection with FIGS. **1**A-**5** above.

[0107] Display device **600** may include a substrate (not shown). The substrate may include any suitable component for supporting pixels and/or any other suitable component of display device **600**. In one implementation, the substrate may include a driver circuit (e.g., one or more CMOS drivers, a TFT, etc.). In another implementation, the substrate does not include a driver circuit. The substrate may include a plurality of conductive lines (e.g., rows and/or columns of conductive lines) connecting one or more of the pixels disposed on the substrate.

[0108] The terms "approximately," "about," and "substantially" may be used to mean within +20% of a target dimension in some embodiments, within +10% of a target dimension in some embodiments, within +5% of a target dimension in some embodiments, and yet within +2% in some embodiments. The terms "approximately" and "about" may include the target dimension.

[0109] In the foregoing description, numerous details are set forth. It will be apparent, however, that the disclosure may be practiced without these specific details. In some instances, well-known structures and devices are shown in block diagram form, rather than in detail, in order to avoid obscuring the disclosure.

[0110] The terms "first," "second," "third," "fourth," etc. as used herein are meant as labels to distinguish among different elements and may not necessarily have an ordinal meaning according to their numerical designation.

[0111] The words "example" or "exemplary" are used herein to mean serving as an example, instance, or illustration. Any aspect or design described herein as "example" or "exemplary" is not necessarily to be construed as preferred or advantageous over other aspects or designs. Rather, use of the words "example" or "exemplary" is intended to present concepts in a concrete fashion. As used in this application, the term "or" is intended to mean an inclusive "or" rather than an exclusive "or". That is, unless specified otherwise, or clear from context, "X includes A or B" is intended to mean any of the natural inclusive permutations. That is, if X includes A; X includes B; or X includes both A and B, then "X includes A or B" is satisfied under any of the foregoing instances. In addition, the articles "a" and "an" as used in this application and the appended claims should generally be construed to mean "one or more" unless specified otherwise or clear from context to be directed to a singular form. Reference throughout this specification to "an implementation" or "one implementation" means that a particular feature, structure, or characteristic described in connection with the implementation is included in at least one implementation. Thus, the appearances of the phrase "an implementation" or "one implementation" in various places throughout this specification are not necessarily all referring to the same implementation.

[0112] As used herein, when an element or layer is referred to as being "on" another element or layer, the element or layer may be directly on the other element or layer, or intervening elements or layers may be present. In contrast, when an element or layer is referred to as being "directly on" another element or layer, there are no intervening elements or layers present.

[0113] Whereas many alterations and modifications of the disclosure will no doubt become apparent to a person of ordinary skill in the art after having read the foregoing description, it is to be understood that any particular embodiment shown and described by way of illustration is in no way intended to be considered limiting. Therefore, references to details of various embodiments are not intended to limit the scope of the claims, which in themselves recite only those features regarded as the disclosure.

What is claimed is:

1. An apparatus, comprising:

a plurality of light-emitting devices for emitting light of a first color; and

a light-emitting device for emitting light of a second color, wherein the light-emitting device for emitting light of the second color is fabricated on a first light-emitting device of the plurality of light-emitting devices for emitting light of the first color.

2. The apparatus of claim **1**, wherein the light-emitting device for emitting light of the second color is electrically connected to a conductive pad, and wherein the first light-emitting device of the plurality of light-emitting devices for emitting light of the first color is bonded to the conductive pad.

3. The apparatus of claim **2**, wherein the light-emitting device for emitting light of the second color is bonded to the first light-emitting device of the plurality of light-emitting devices for emitting light of the first color.

4. The apparatus of claim **3**, further comprising a conductive via fabricated in the first light-emitting device of the plurality of light-emitting devices for emitting light of the first color.

5. The apparatus of claim **3**, a sidewall of the first light-emitting device of the plurality of light-emitting devices for emitting light of the first color is coated with a conductive material.

6. The apparatus of claim **5**, wherein the light-emitting device for emitting light of the second color is electrically connected to the conductive pad through the conductive material.

7. The apparatus of claim **1**, further comprising:

a light-conversion structure that converts light emitted by a second light-emitting device of the plurality of light-emitting devices for emitting light of the first color into light of a third color.

8. The apparatus of claim **7**, wherein the light-conversion structure comprises a plurality of quantum dots.

9. The apparatus of claim **8**, further comprising an electrode layer, wherein the electrode layer is fabricated on the light-emitting device for emitting light of the second color, the second light-emitting device of the plurality of light-emitting devices for emitting light of the first color, and a third light-emitting device of the plurality of light-emitting devices for emitting light of the first color.

10. The apparatus of claim **9**, further comprising a plurality of metal sidewalls fabricated on the electrode layer.

11. The apparatus of claim **1**, further comprising a substrate, wherein the plurality of light-emitting devices for emitting light of the first color is bonded to the substrate.

12. A method, comprising:

fabricating, in a first light-emitting stack configured to emit light of a first color, a conductive via;

fabricating, on the conductive via, a light-emitting device for emitting light of a second color;

selectively removing one or more portions of the first light-emitting stack to fabricate a plurality of light-emitting devices for emitting light of the first color, wherein the light-emitting device for emitting light of the second color is fabricated on a first light-emitting device of the plurality of light-emitting devices for emitting light of the first color.

13. The method of claim **12**, wherein fabricating the conductive via in the first light-emitting stack comprises creating an opening in the first light-emitting stack and depositing a metallic material in the opening.

14. The method of claim **13**, wherein the first light-emitting stack is bonded to a substrate prior to fabricating the conductive via.

15. The method of claim **12**, further comprising fabricating a light-conversion structure on a second light-emitting device of the plurality of light-emitting devices for emitting light of the first color.

16. The method of claim **15**, wherein the light-conversion structure comprises a plurality of quantum dots.

17. The method of claim **12**, wherein fabricating, on the conductive via, the light-emitting device for emitting light of the second color comprises:

bonding a second light-emitting stack to the first light-emitting stack and the conductive via; and

selectively removing one or more portions of the second light-emitting stack to form the light-emitting device for emitting light of the second color.

18. The method of claim **12**, further comprising fabricating an electrode layer, wherein the electrode layer provides ohmic contact for the light-emitting device for emitting light of the second color and the second light-emitting device of the plurality of light-emitting devices for emitting light of the first color.

19. The method of claim **18**, further comprising bonding a light-conversion structure to the electrode layer.

20. The method of claim **12**, wherein the first light-emitting stack comprises a plurality of epitaxial layers of a group III-V material.

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