



US 20210367112A1

(19) **United States**(12) **Patent Application Publication****Bergmann et al.**(10) **Pub. No.: US 2021/0367112 A1**(43) **Pub. Date: Nov. 25, 2021**(54) **WAFER LEVEL PACKAGING OF MULTIPLE LIGHT EMITTING DIODES (LEDs) ON A SINGLE CARRIER DIE***H01L 33/22* (2006.01)*H01L 33/00* (2006.01)*H01L 33/62* (2006.01)*H01L 33/48* (2006.01)*H01L 33/60* (2006.01)(71) Applicant: **CreeLED, Inc.**, Durham, NC (US)(72) Inventors: **Michael John Bergmann**, Raleigh, NC (US); **Kevin Haberern**, Cary, NC (US); **Alan Wellford Dillon**, Bahama, NC (US)(52) **U.S. Cl.**CPC ..... *H01L 33/50* (2013.01); *H01L 33/405* (2013.01); *H01L 24/94* (2013.01); *H01L 33/22* (2013.01); *H01L 33/0095* (2013.01); *H01L 33/62* (2013.01); *H01L 33/486* (2013.01); *H01L 33/0093* (2020.05); *H01L 33/60* (2013.01); *H01L 2224/14131* (2013.01); *H01L 2224/81895* (2013.01); *H01L 2224/14155* (2013.01); *H01L 2924/12042* (2013.01); *H01L 24/81* (2013.01); *H01L 24/14* (2013.01)(21) Appl. No.: **17/325,970**(22) Filed: **May 20, 2021****Related U.S. Application Data**

(63) Continuation of application No. 15/493,735, filed on Apr. 21, 2017, now abandoned, which is a continuation of application No. 13/801,743, filed on Mar. 13, 2013, now Pat. No. 9,666,764, which is a continuation-in-part of application No. 13/608,397, filed on Sep. 10, 2012, now Pat. No. 9,653,643.

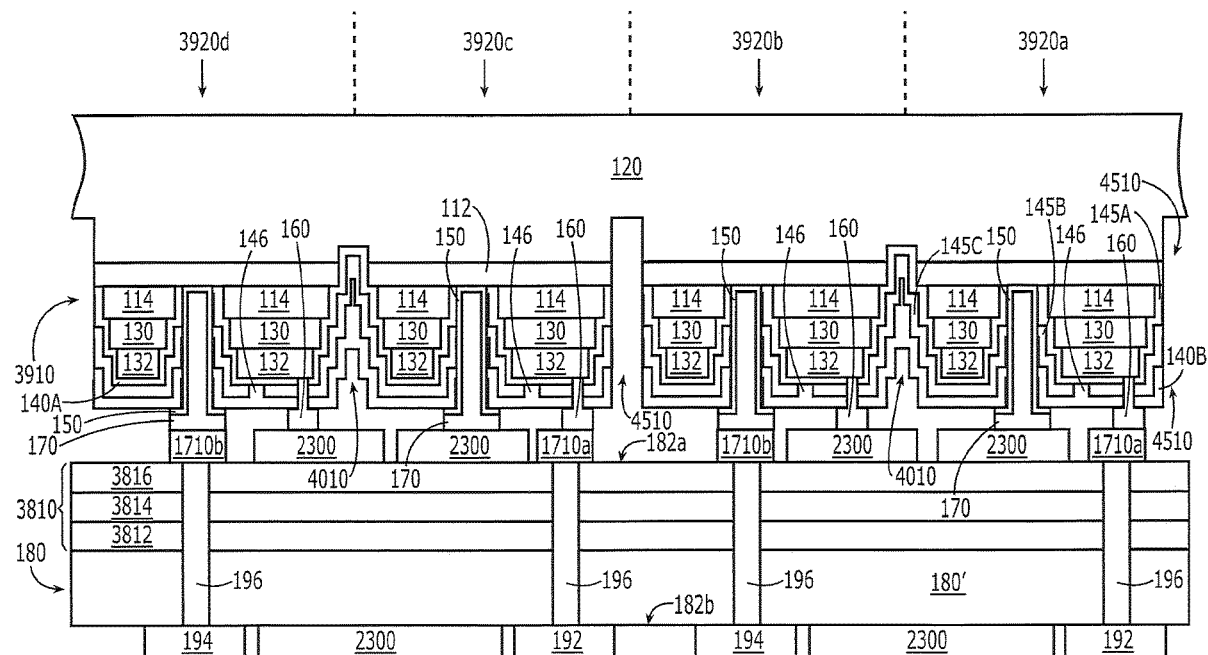
(60) Provisional application No. 61/621,746, filed on Apr. 9, 2012, provisional application No. 61/727,524, filed on Nov. 16, 2012.

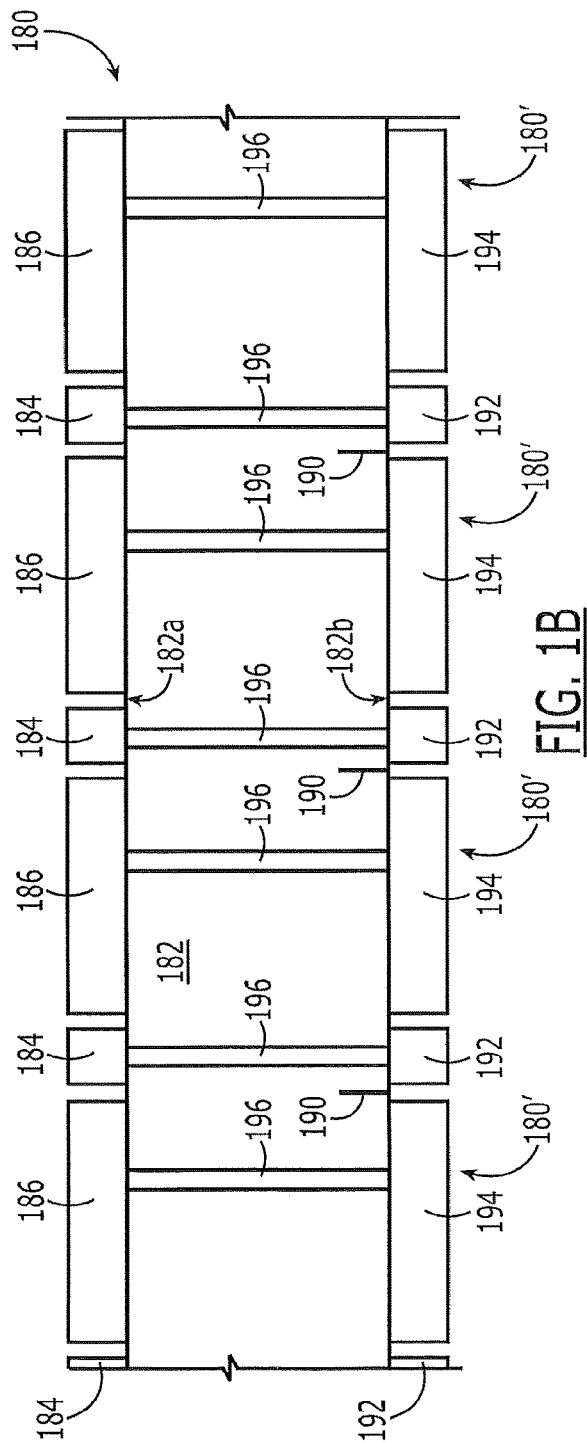
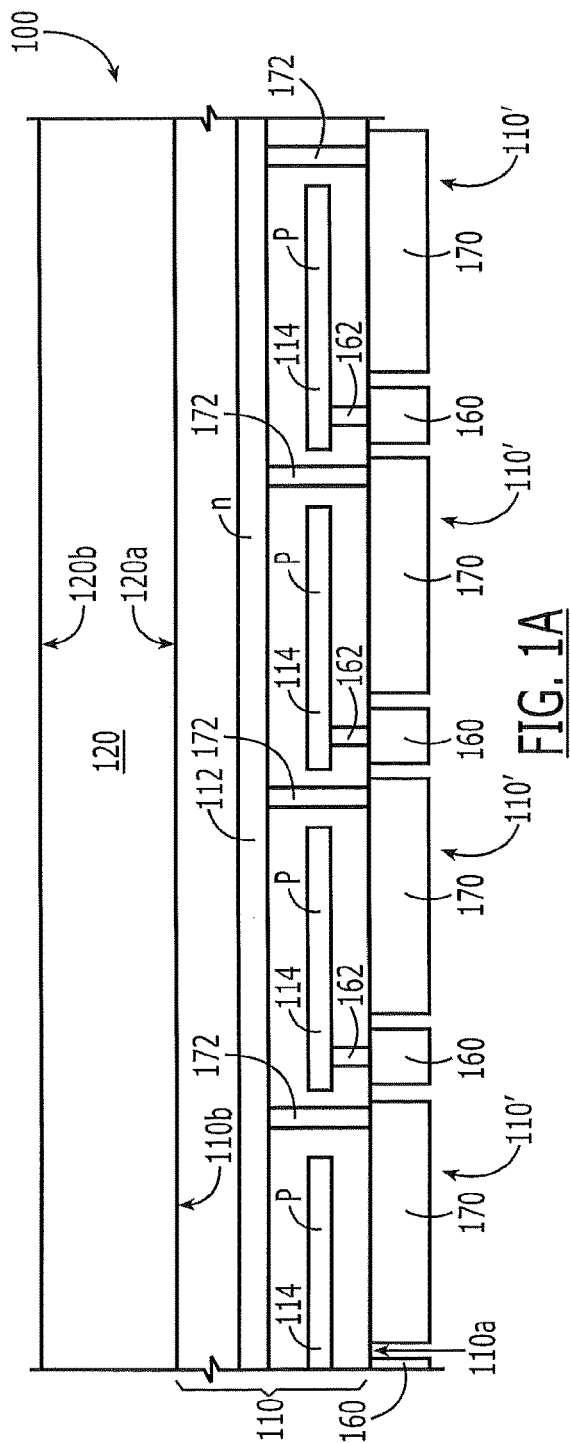
**Publication Classification**(51) **Int. Cl.***H01L 33/50* (2006.01)*H01L 23/00* (2006.01)

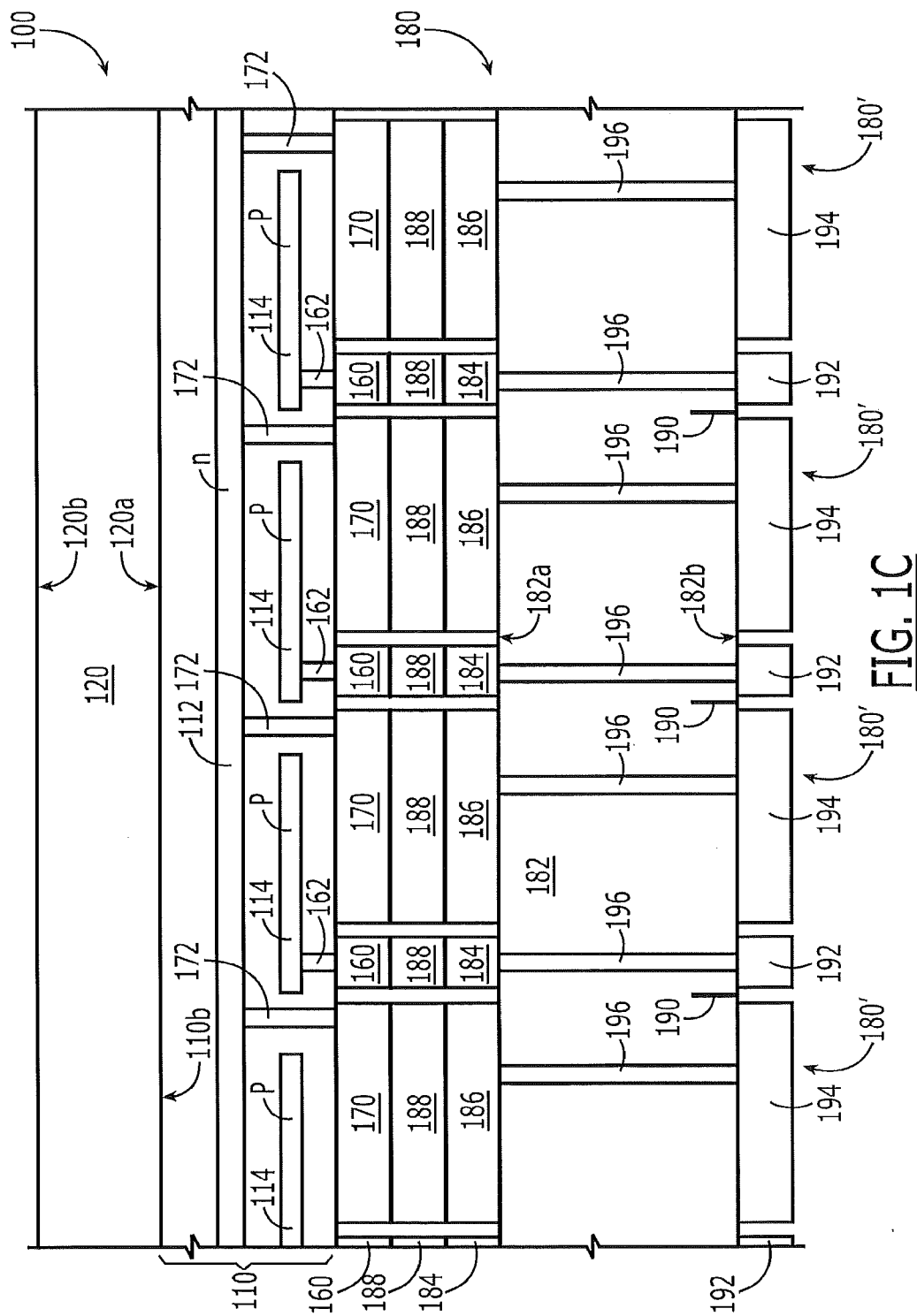
(57)

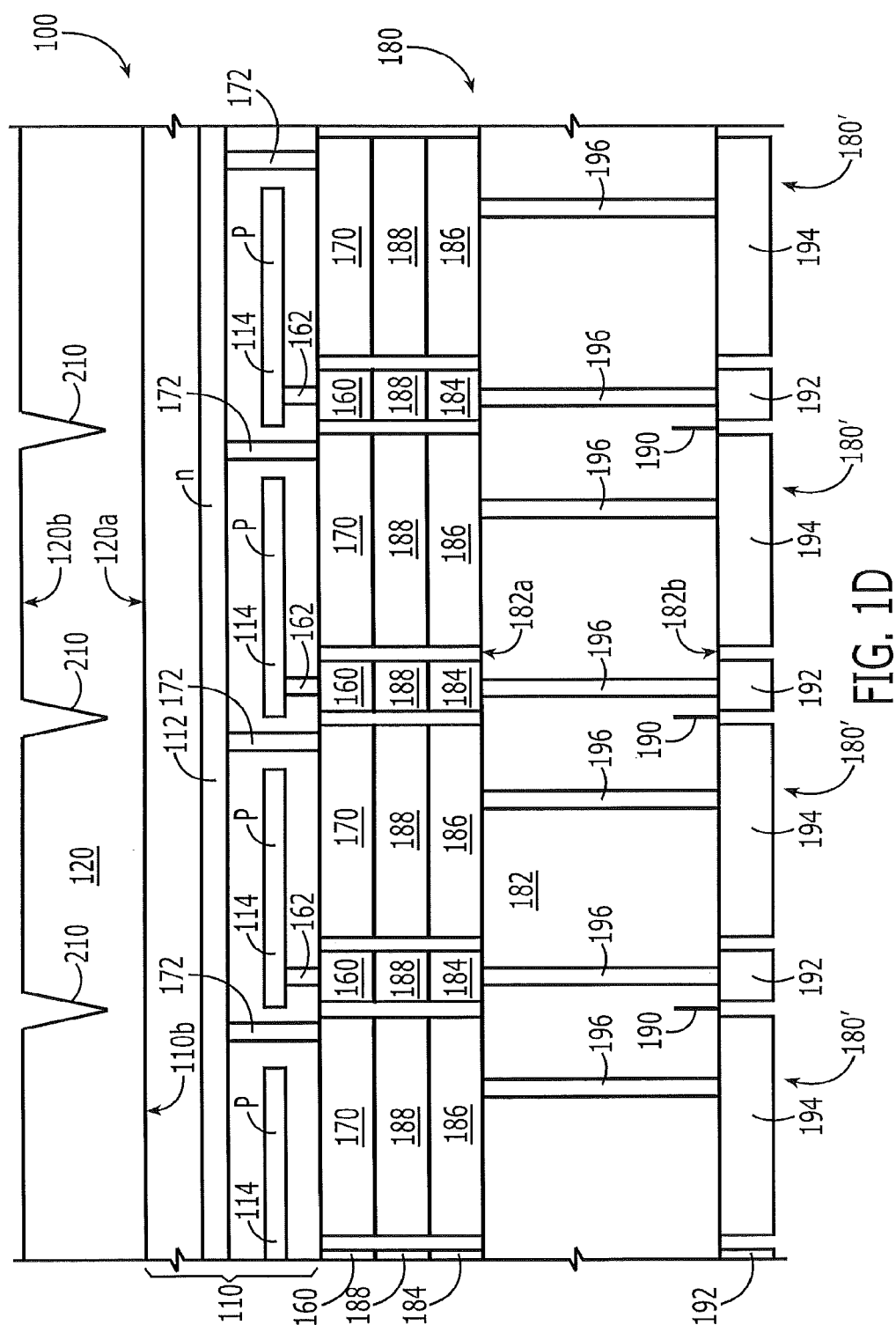
**ABSTRACT**

An LED wafer includes LED dies on an LED substrate. The LED wafer and a carrier wafer are joined. The LED wafer that is joined to the carrier wafer is shaped. Wavelength conversion material is applied to the LED wafer that is shaped. Singulation is performed to provide multiple LED dies that are joined to a single carrier die. The multiple LED dies on the single carrier die are connected in series and/or in parallel by interconnection in the LED dies and/or in the single carrier die. The singulated devices may be mounted in an LED fixture to provide high light output per unit area. Related devices and fabrication methods are described.

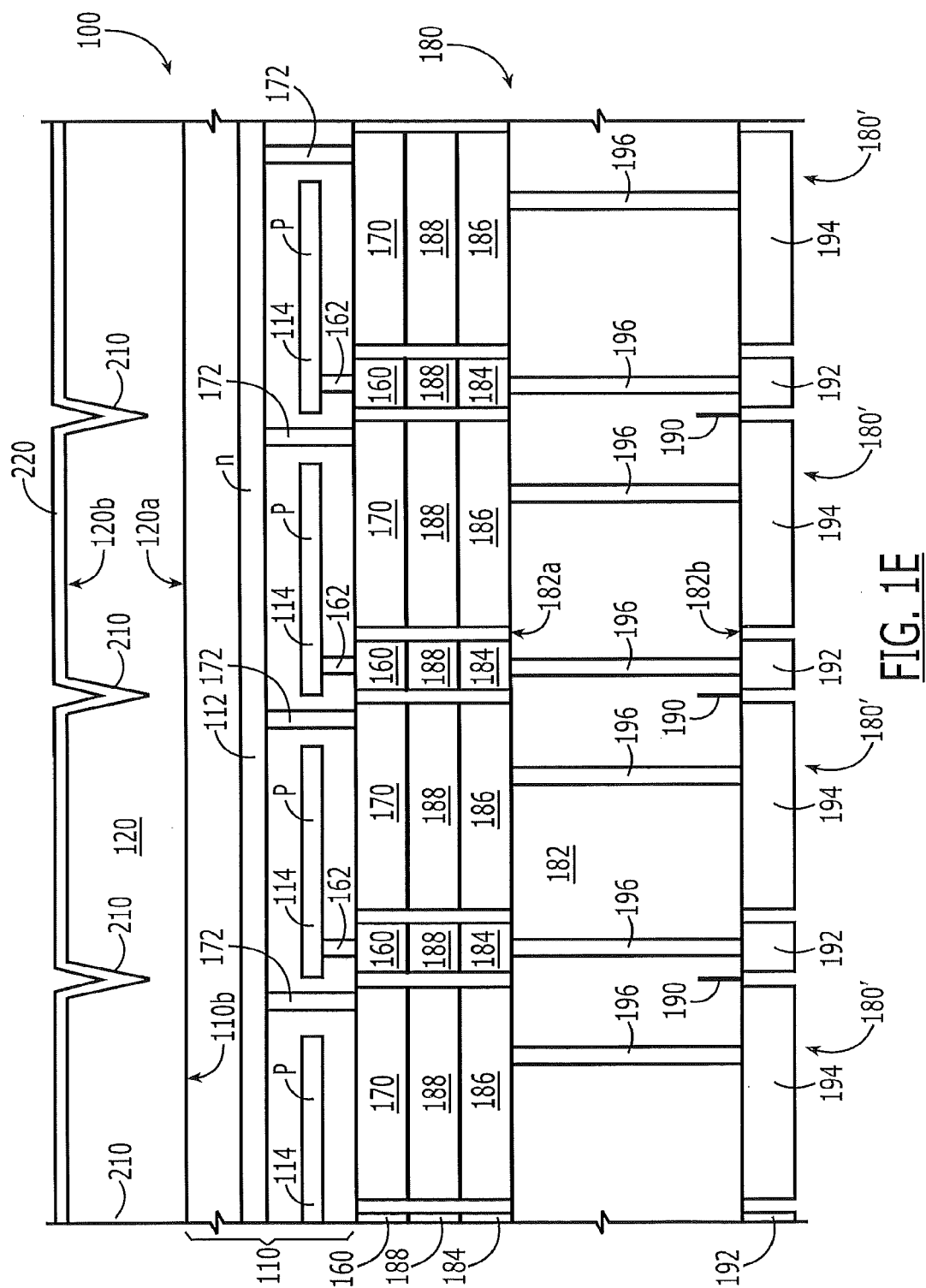


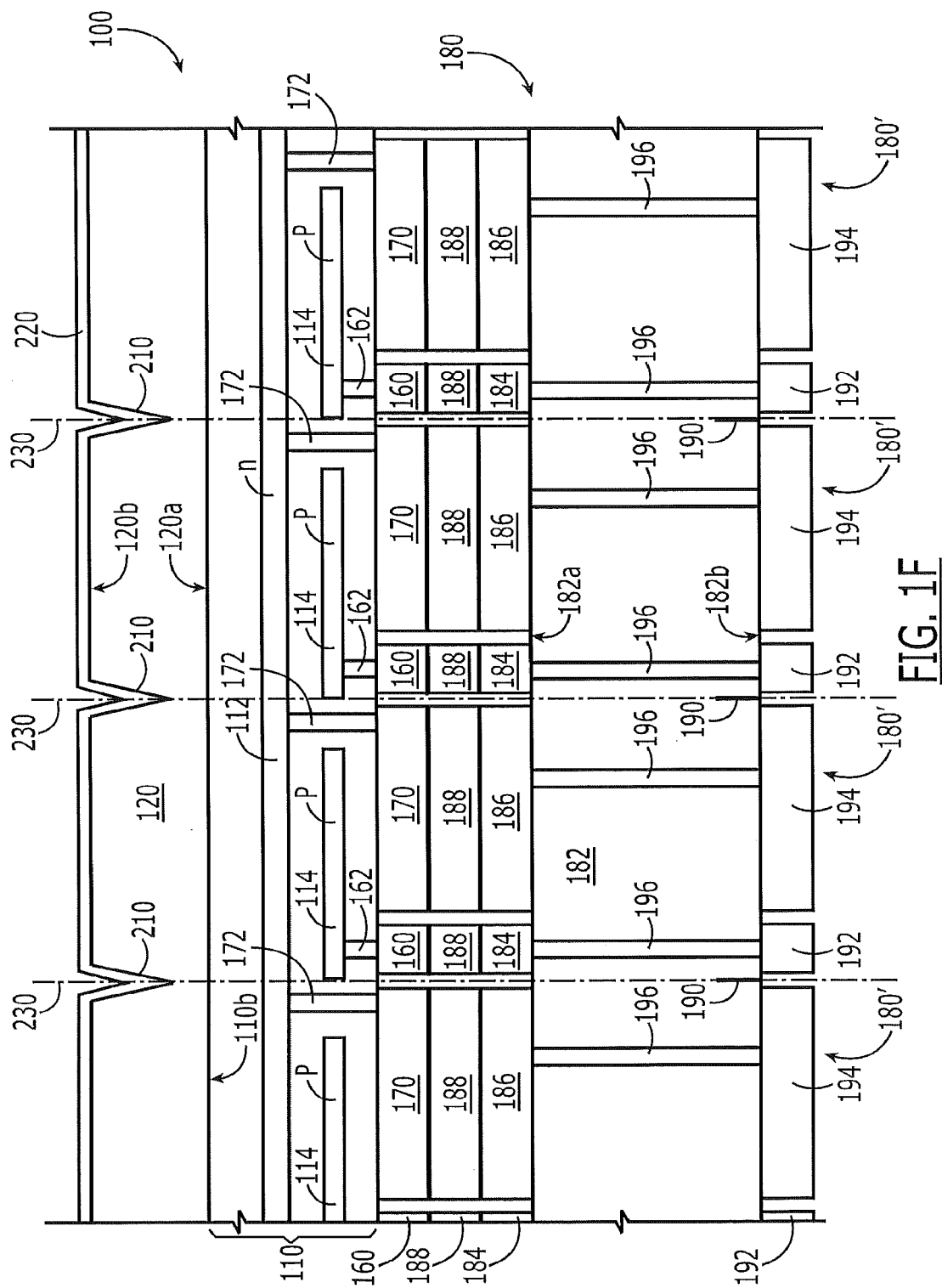


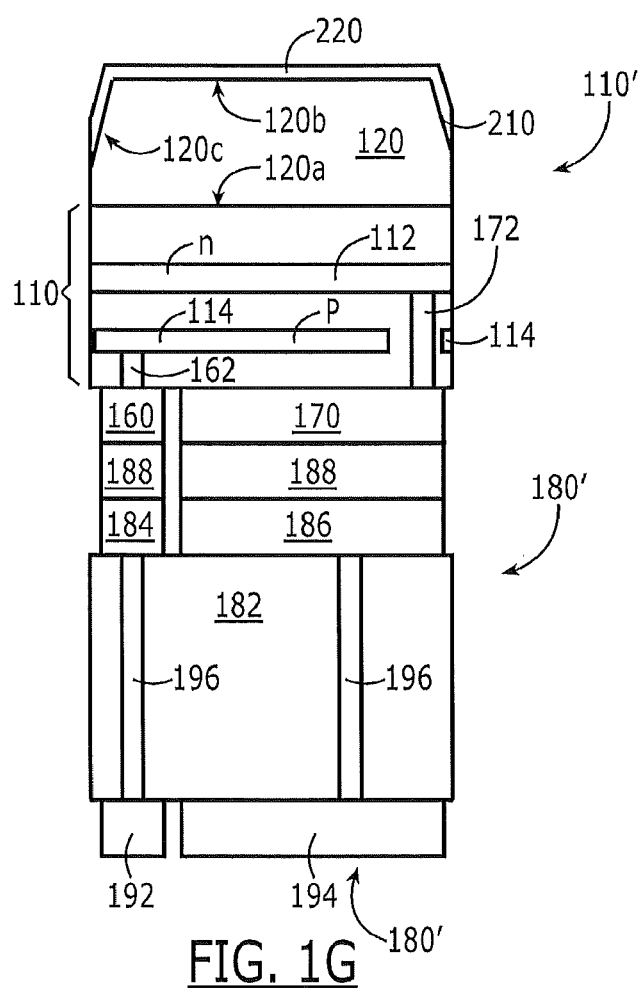


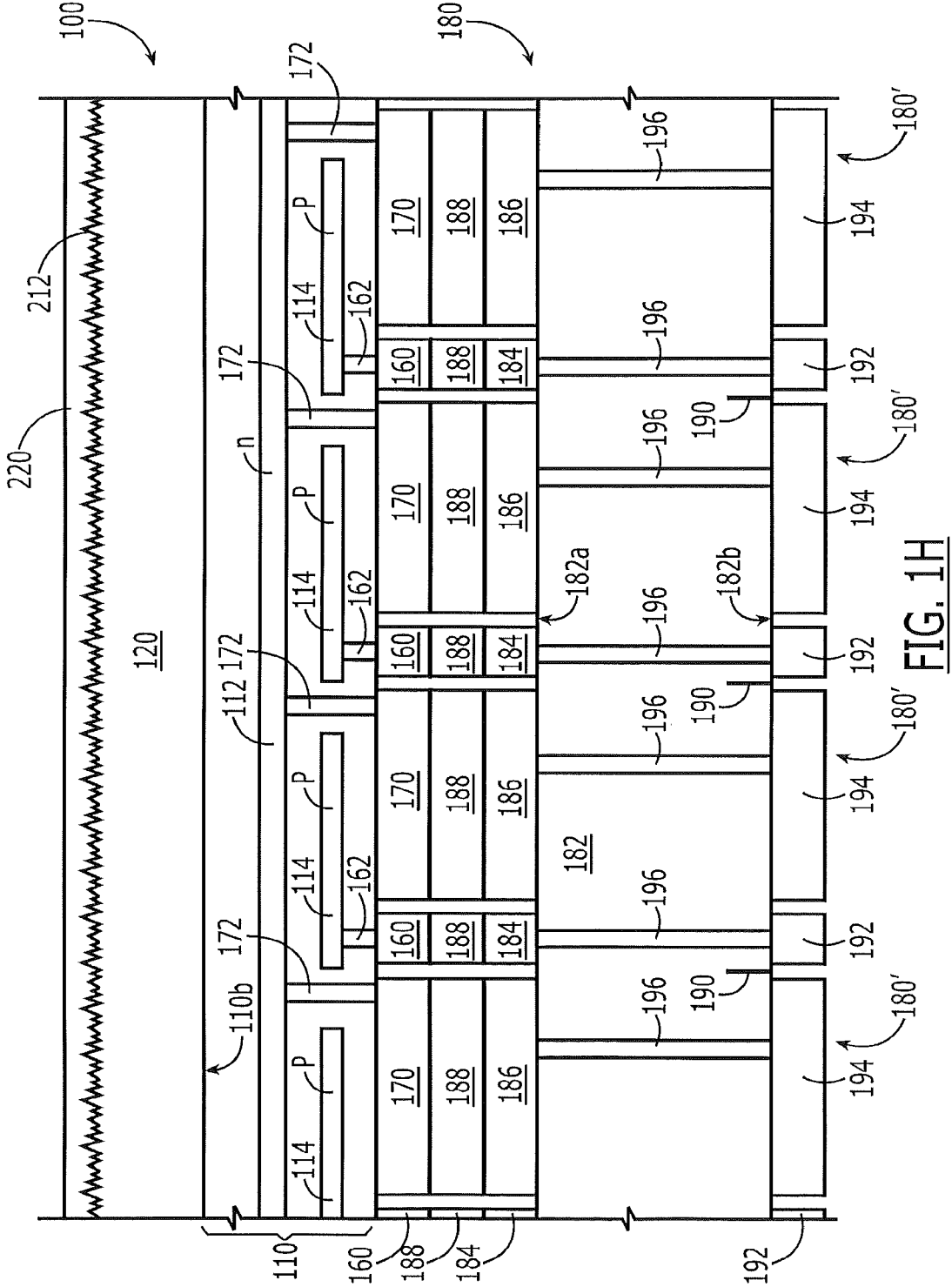


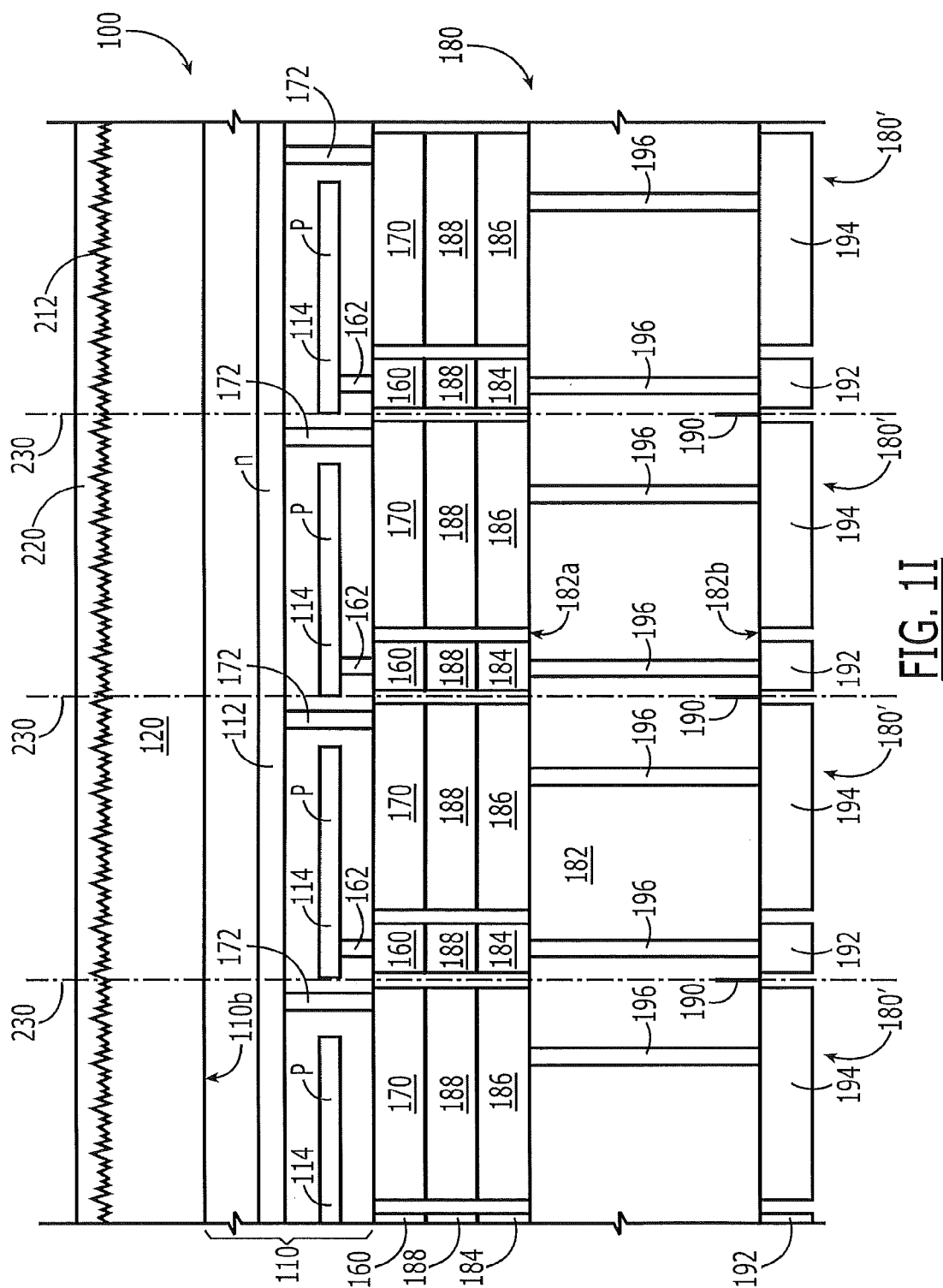












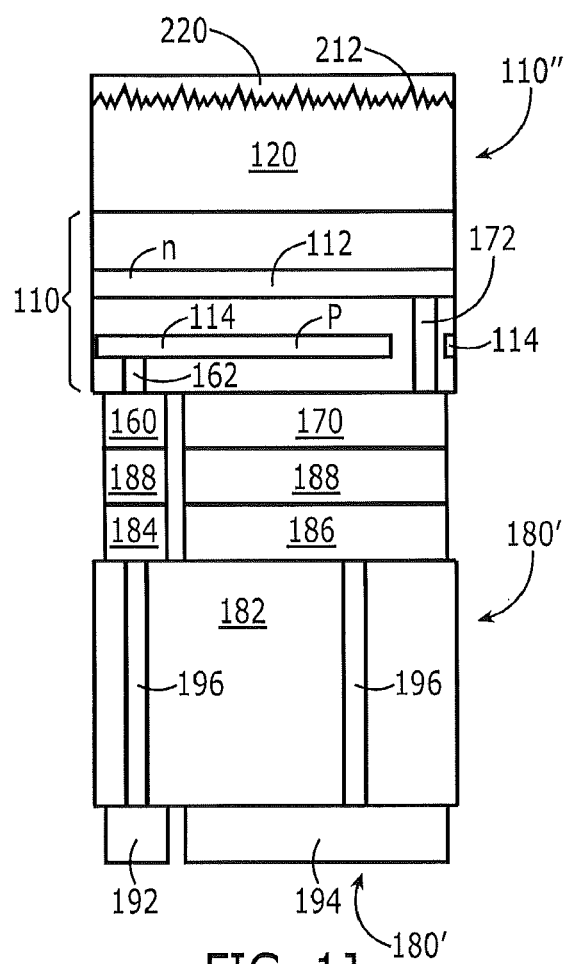
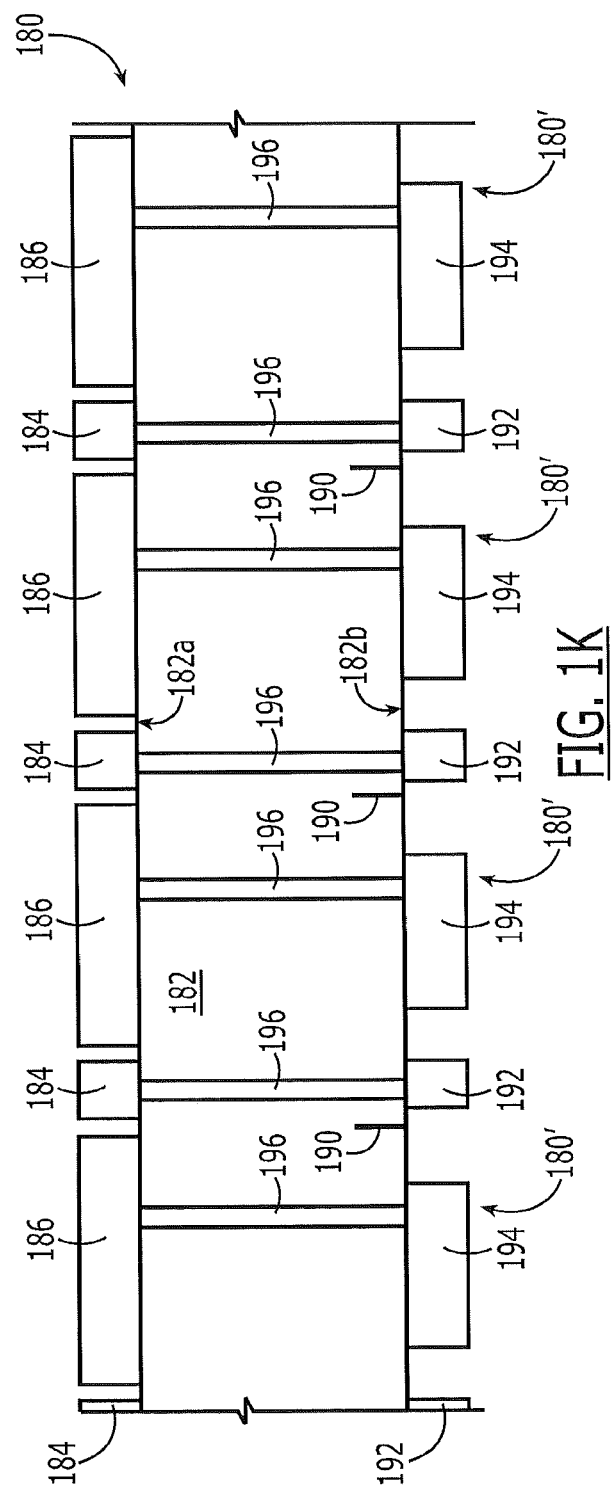
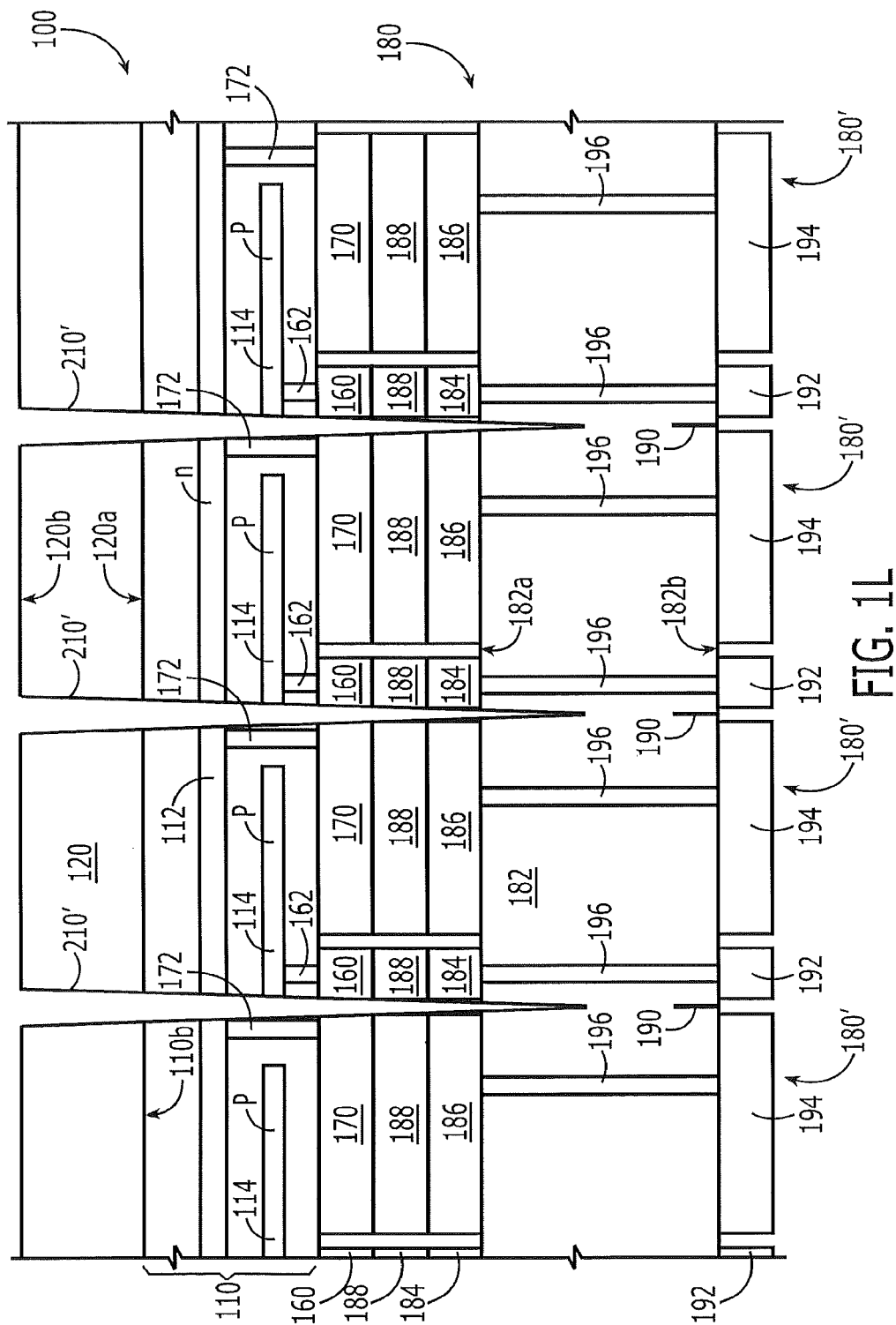
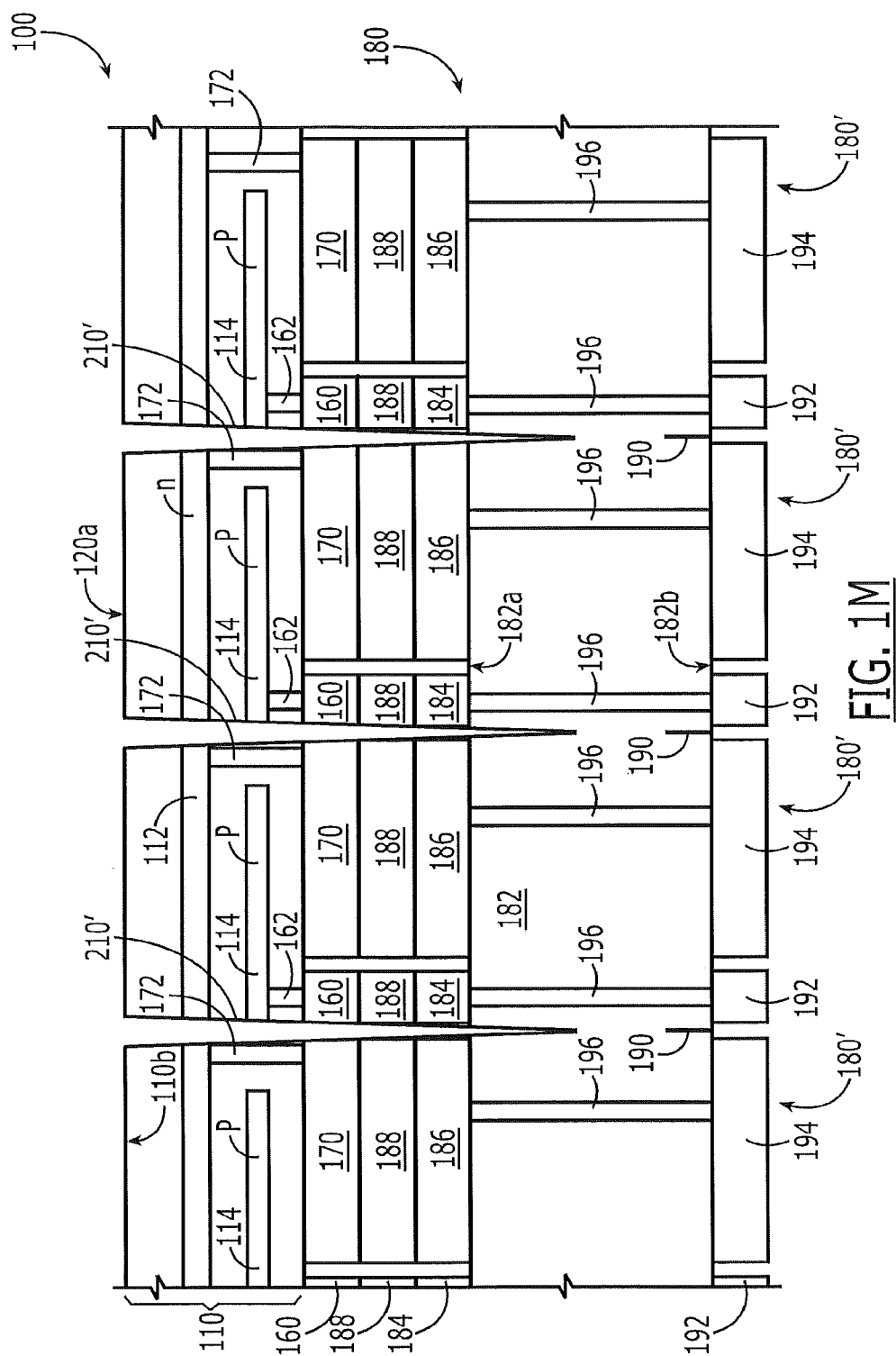


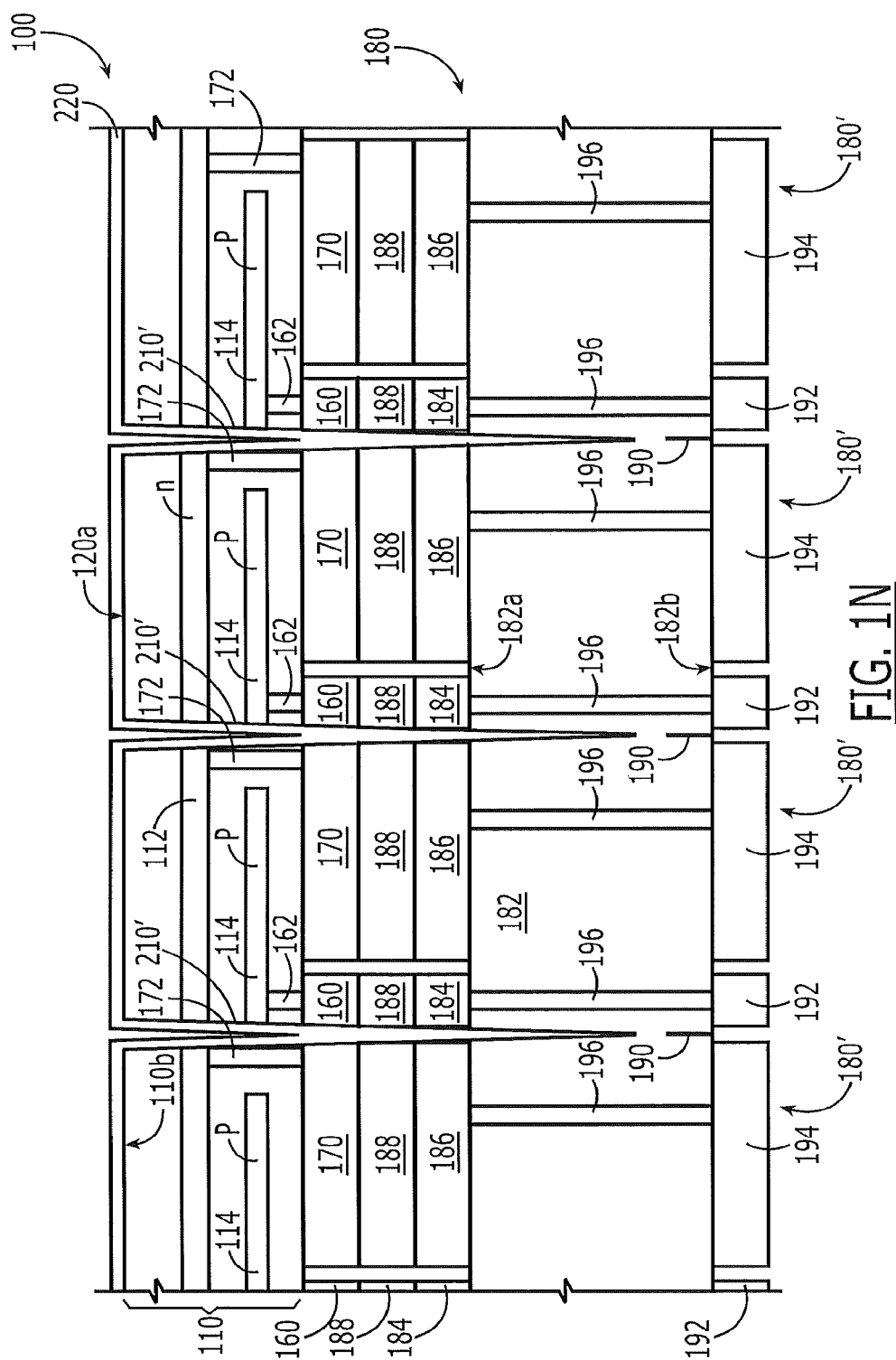
FIG. 1J











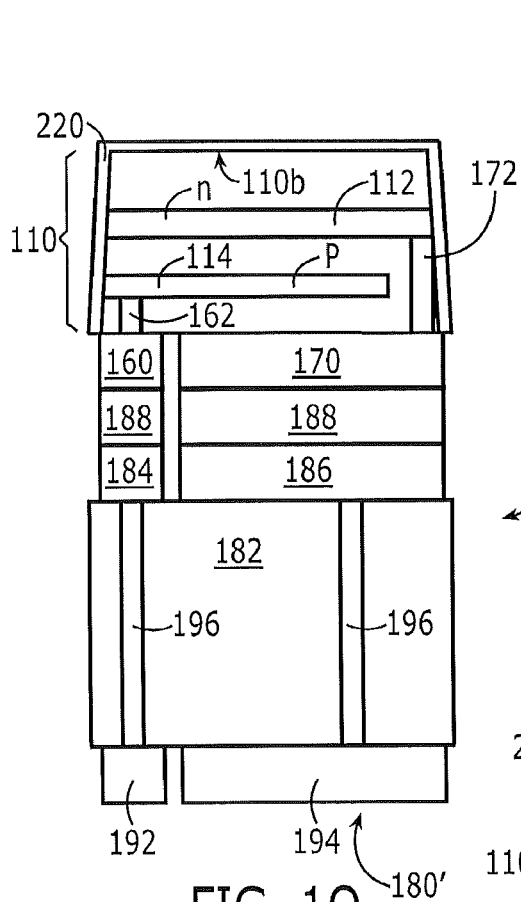


FIG. 10

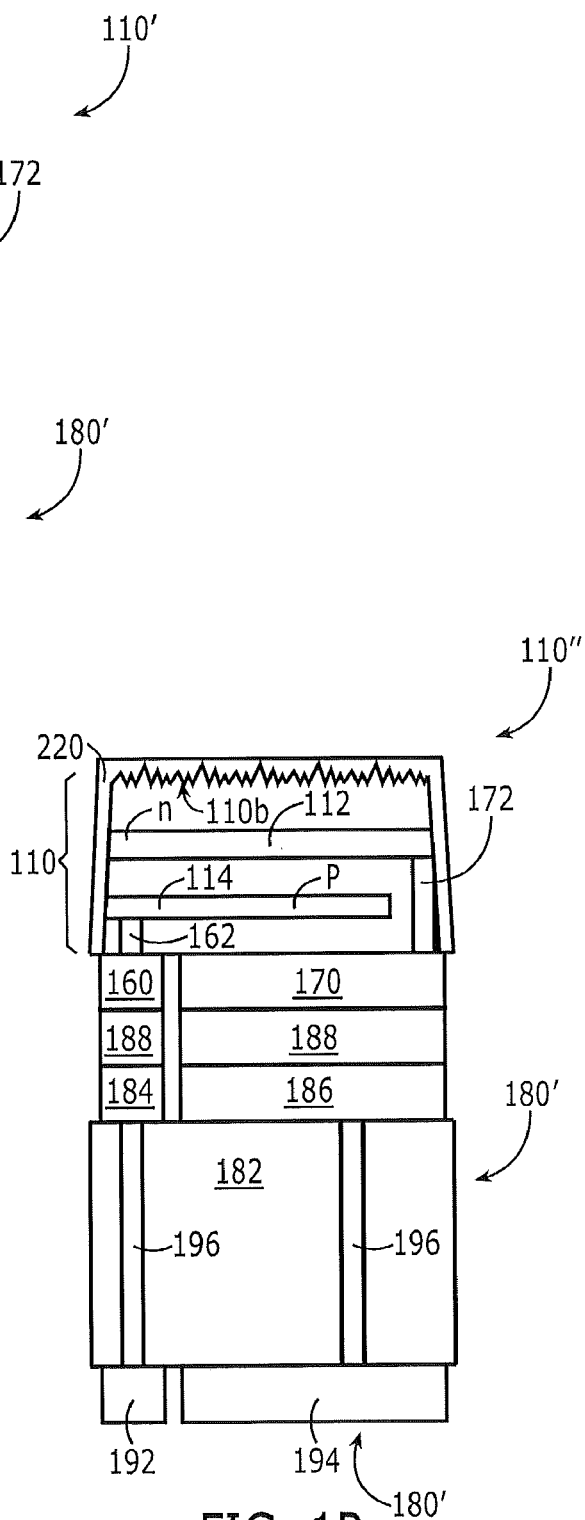
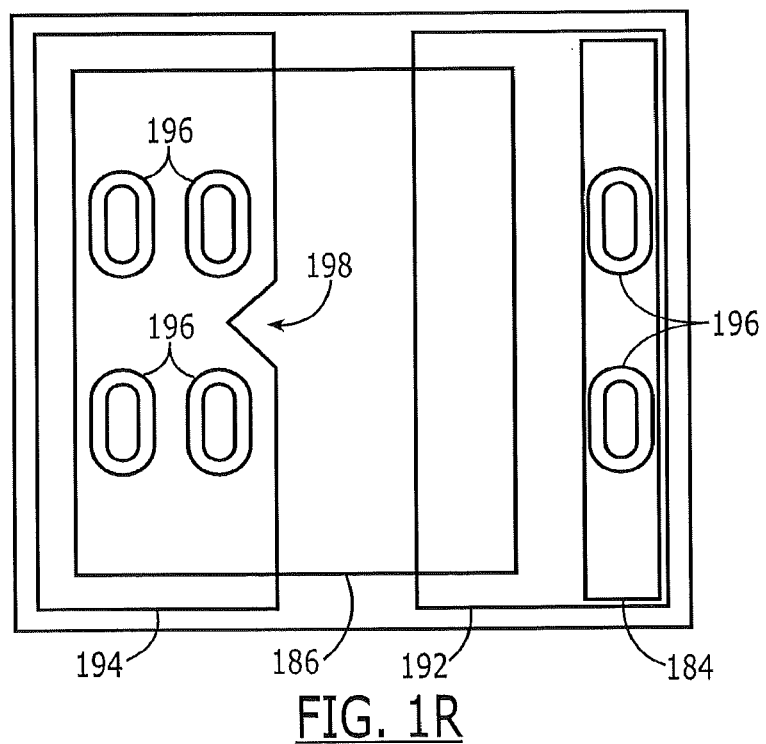
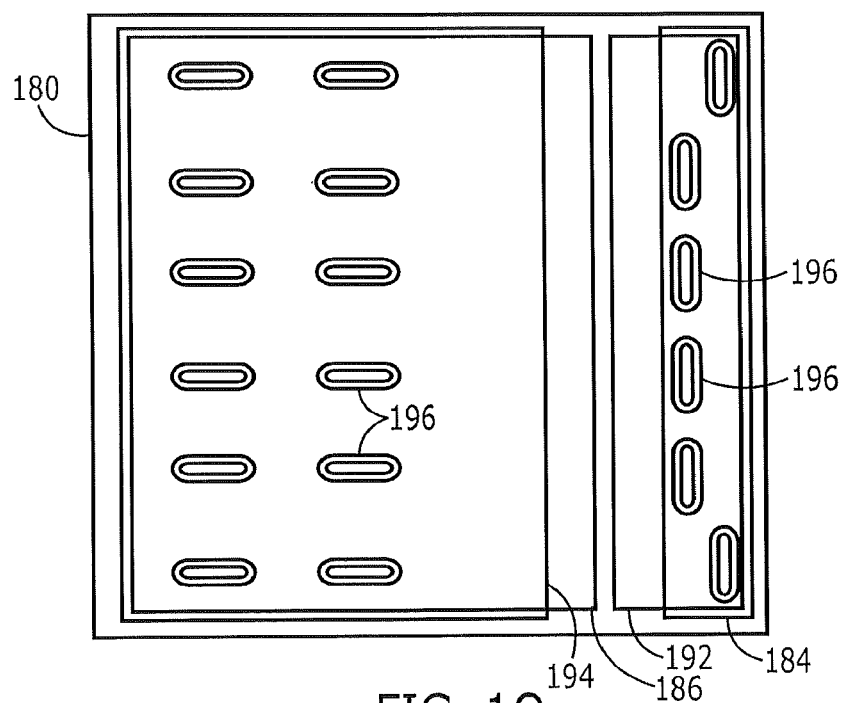


FIG. 1P



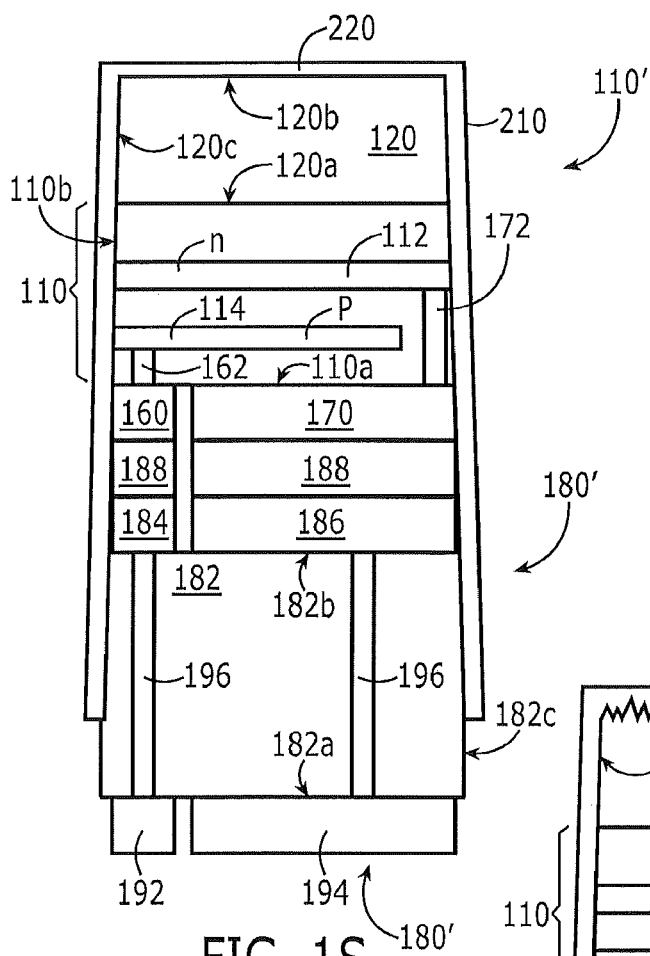


FIG. 1S

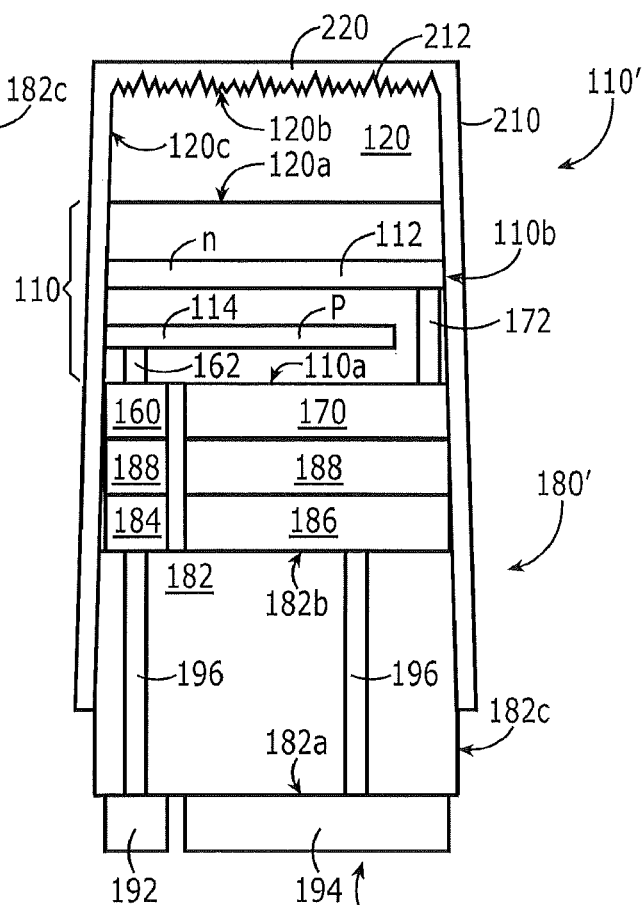
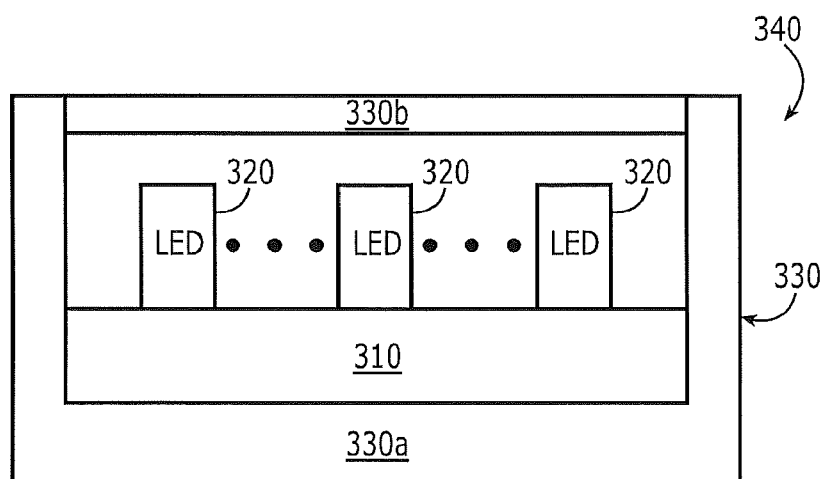
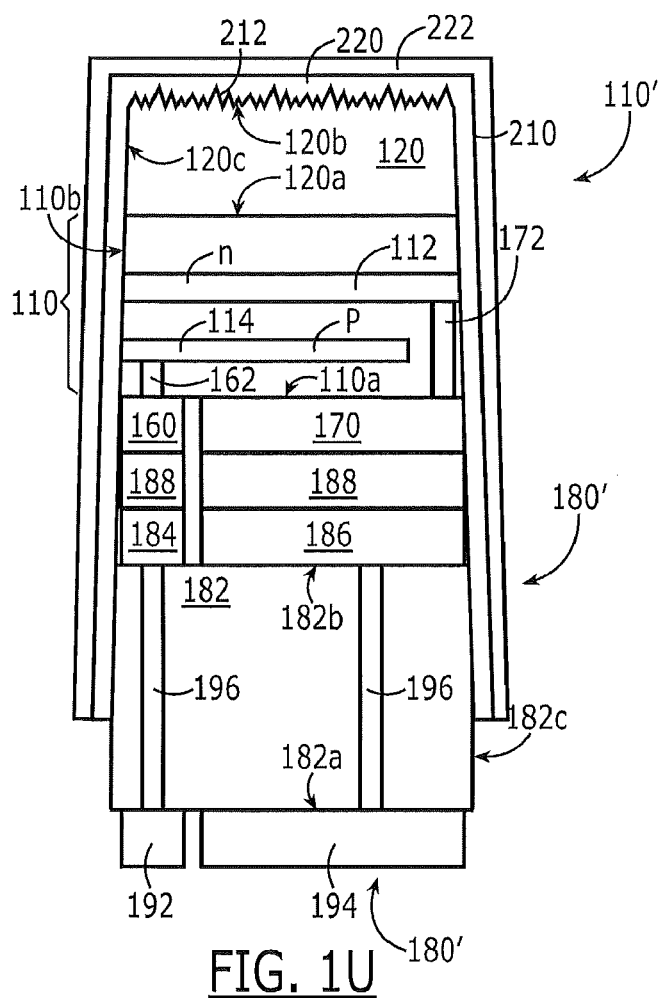


FIG. 1T



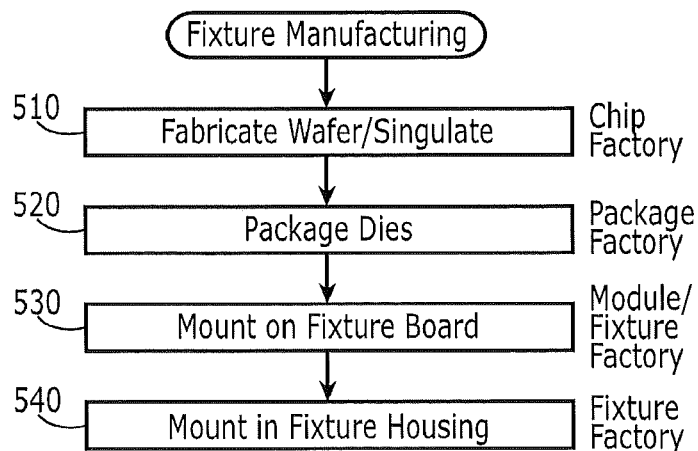
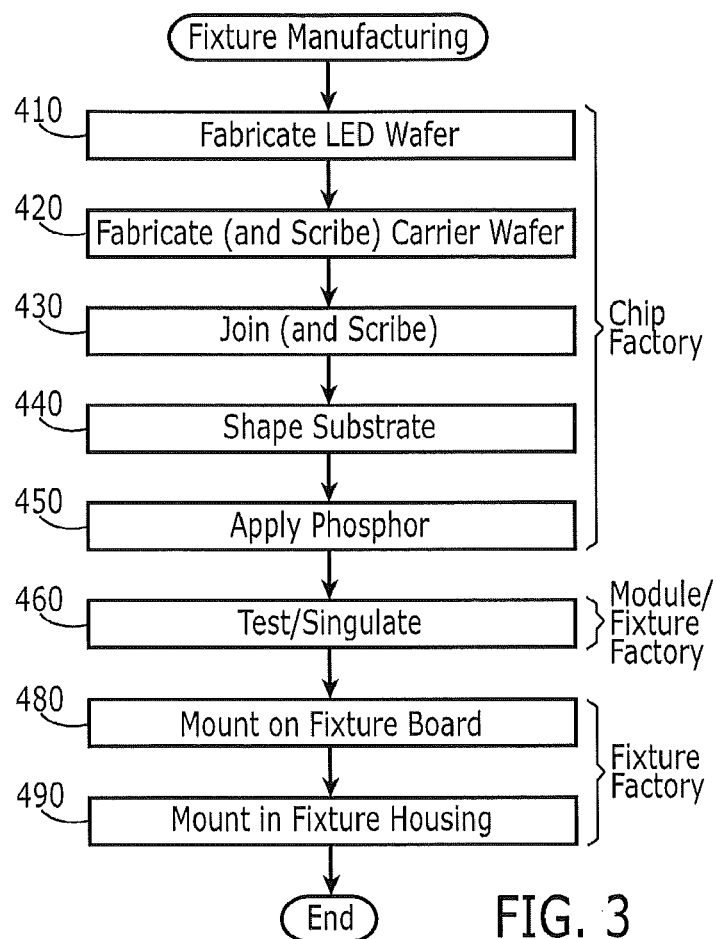
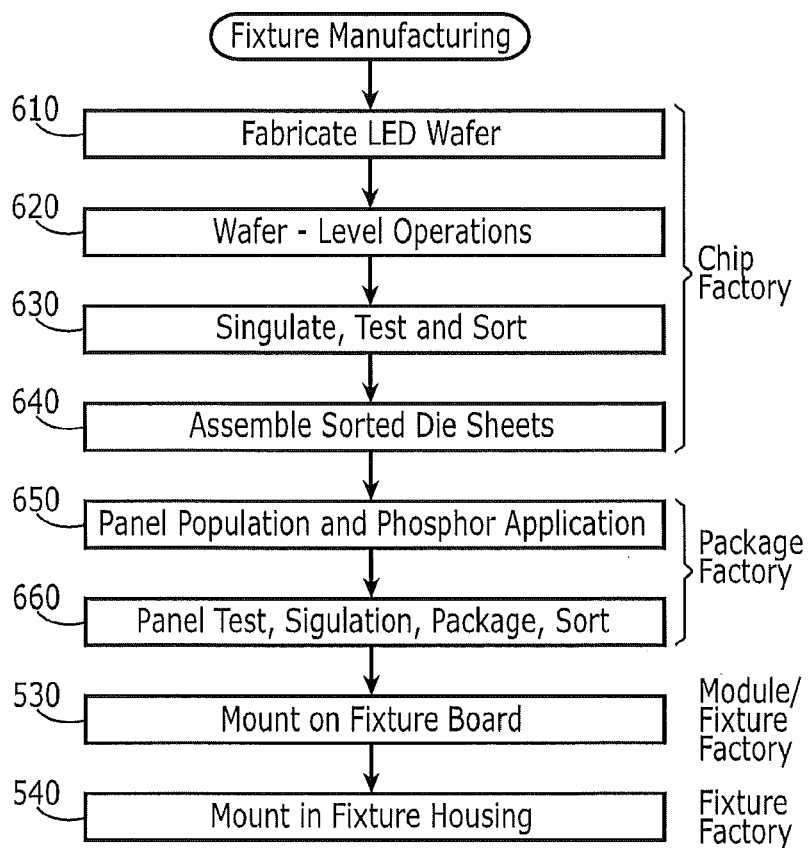


FIG. 4  
(PRIOR ART)



**FIG. 5**  
(PRIOR ART)



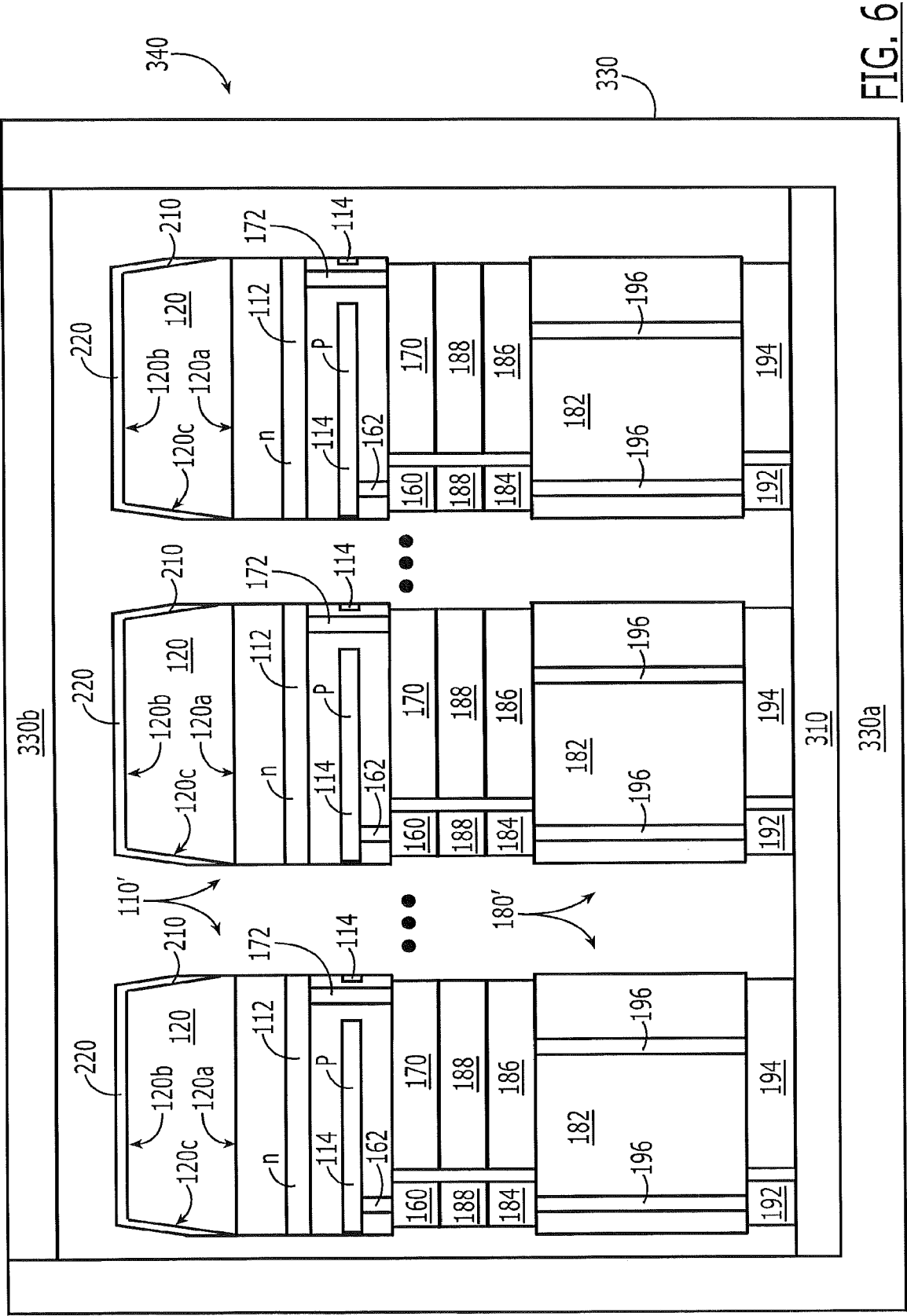


FIG. 6

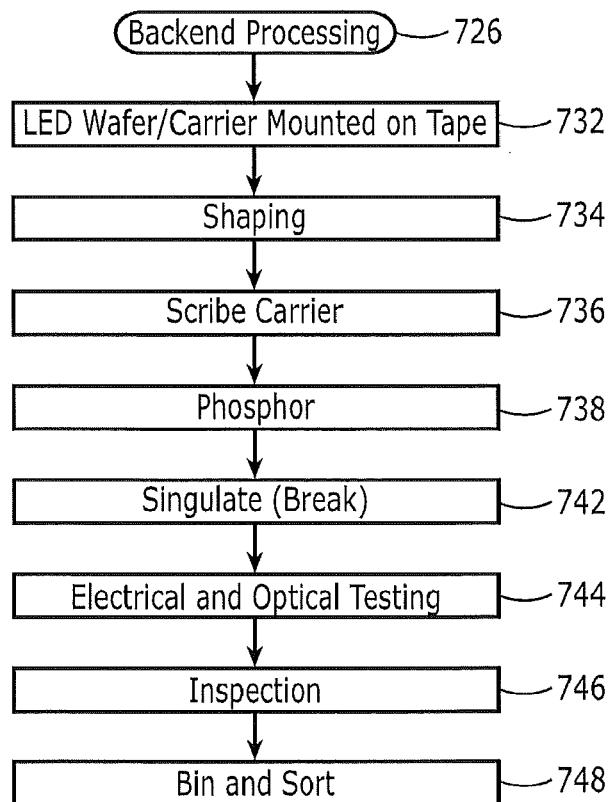
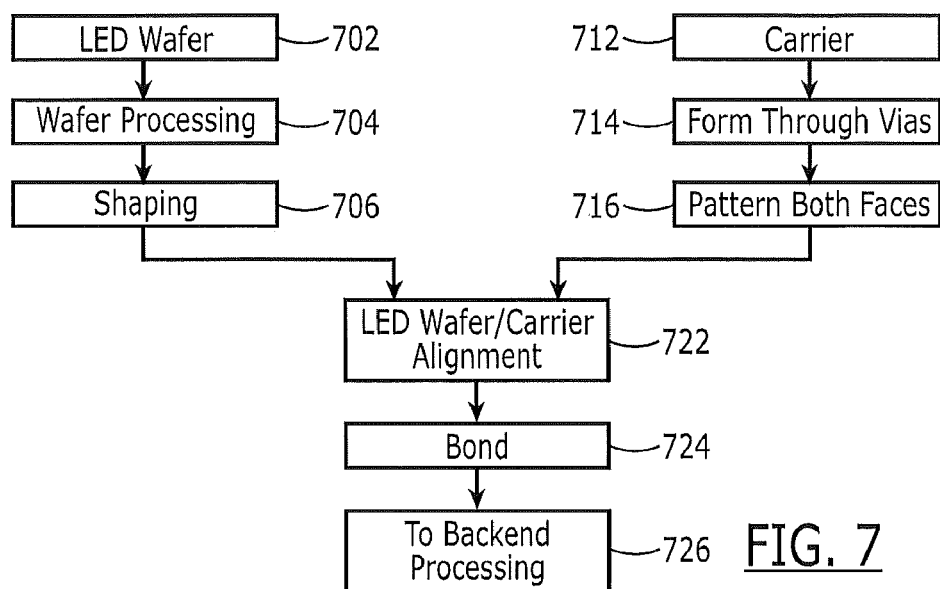
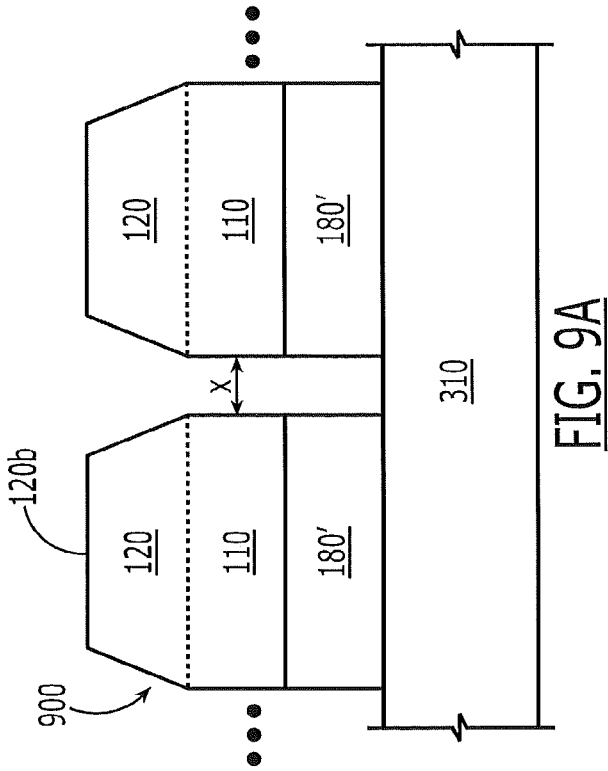
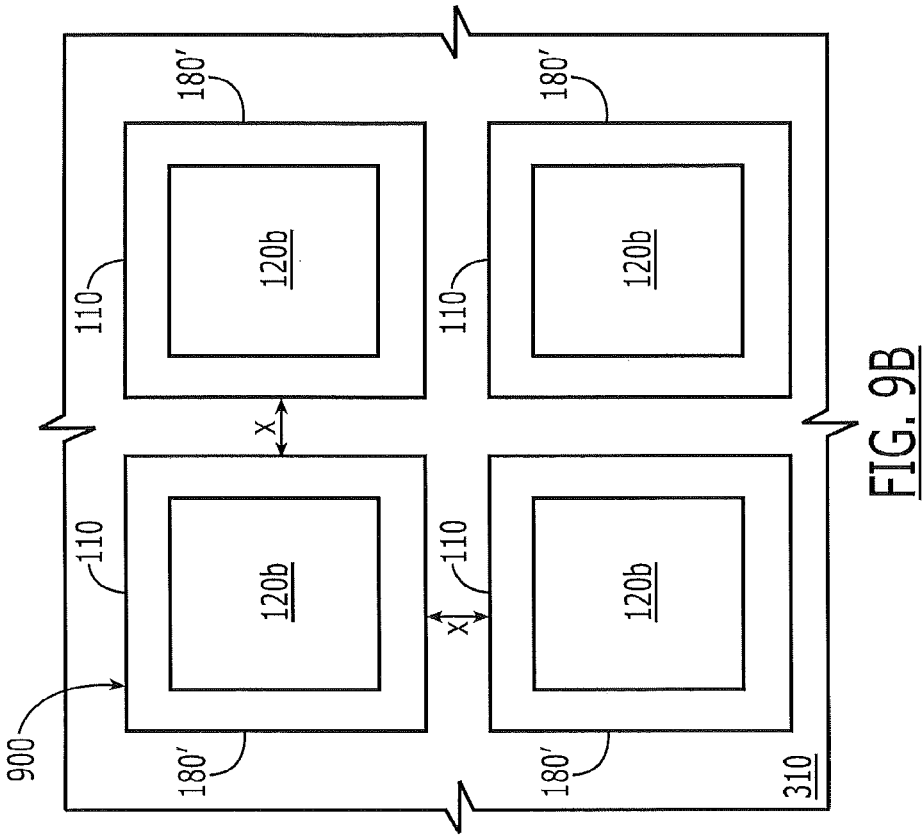
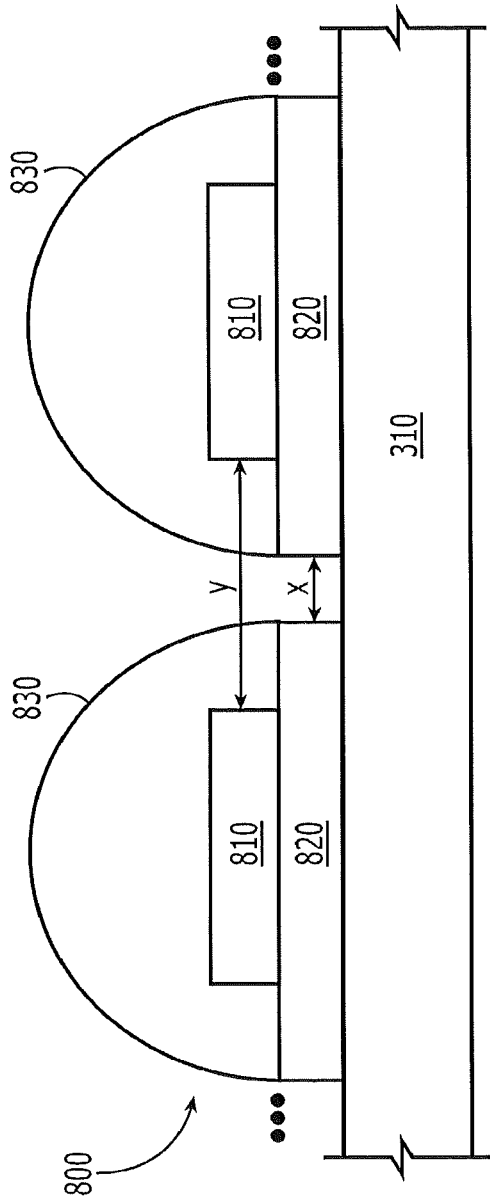


FIG. 8





**FIG. 10A**  
(PRIOR ART)

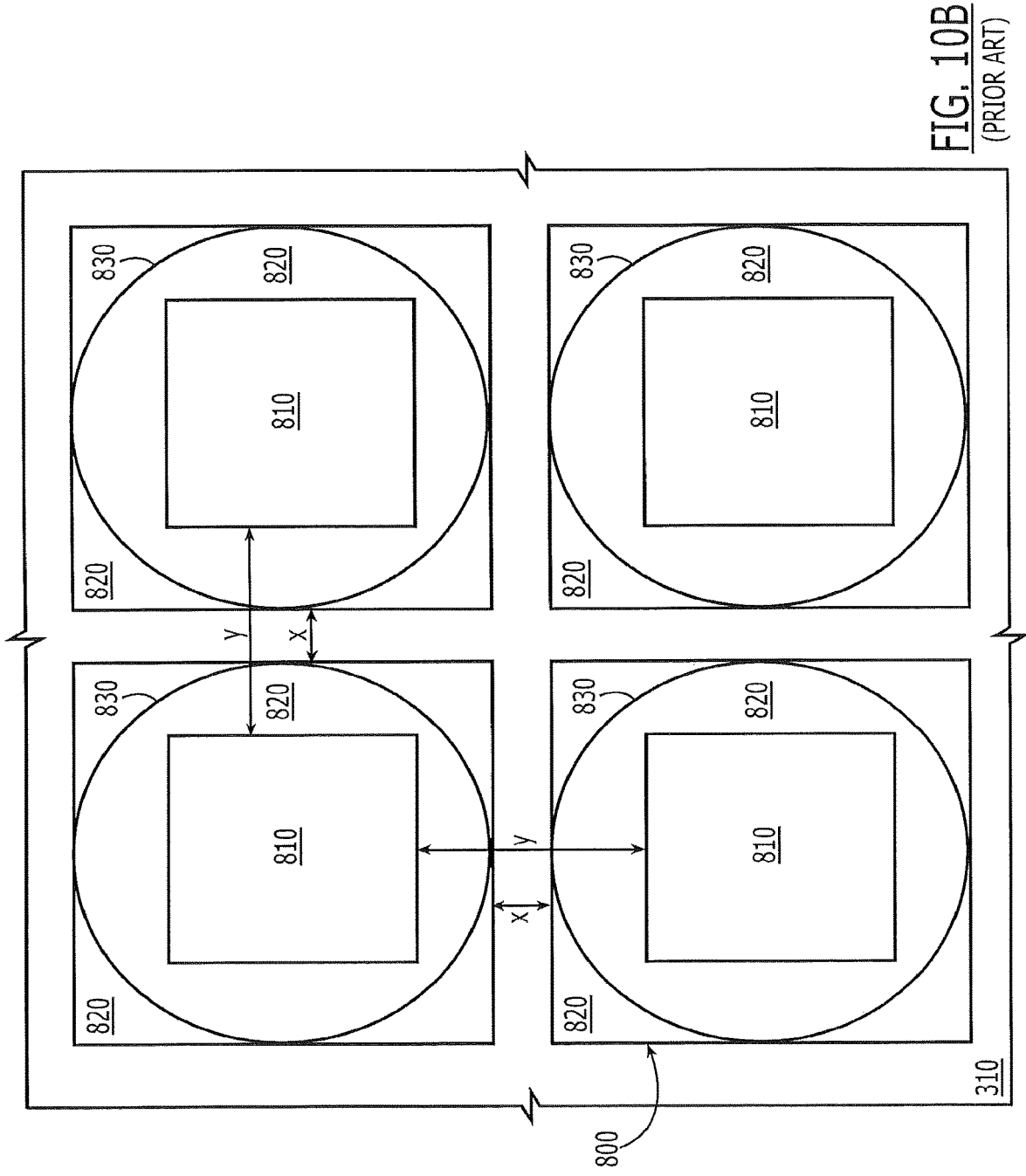


FIG. 10B  
(PRIOR ART)

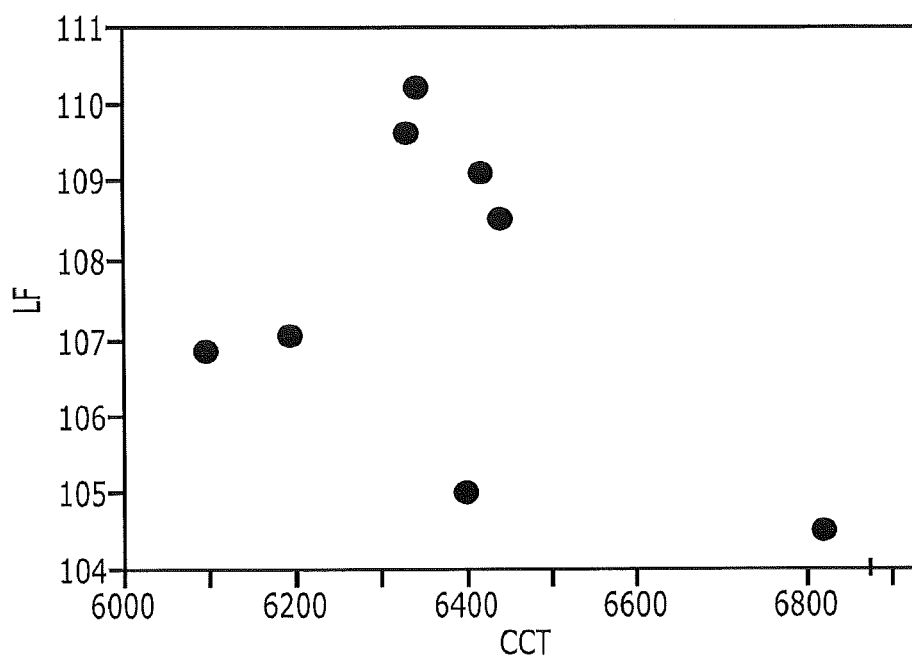


FIG. 11

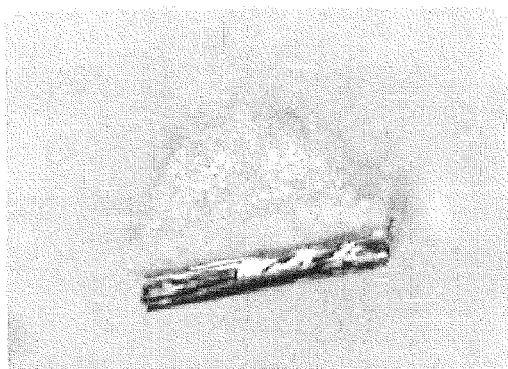


FIG. 12A

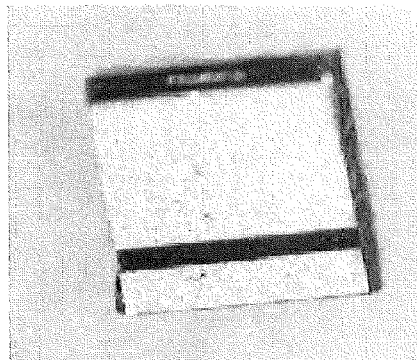


FIG. 12B

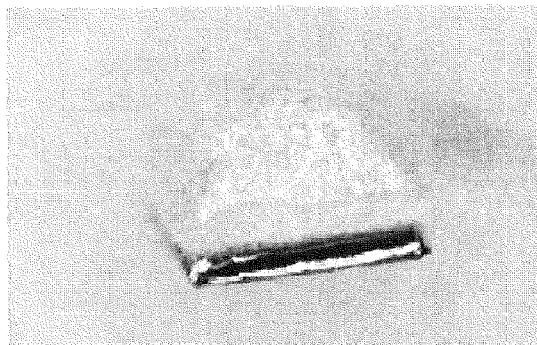


FIG. 12C

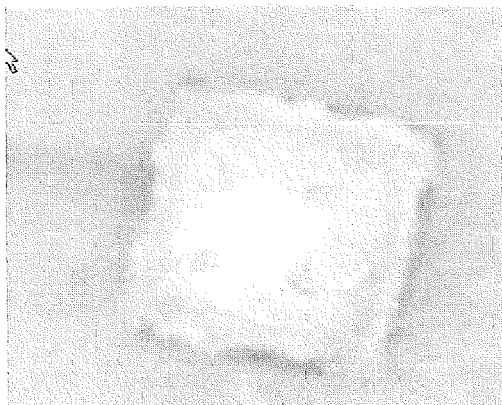


FIG. 12D

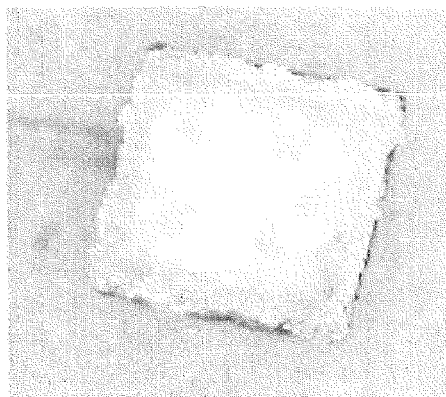
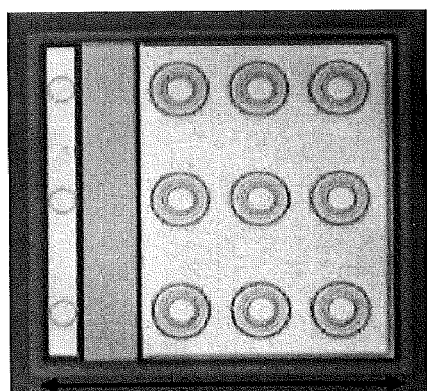


FIG. 12E



0.7mm  
FIG. 13A

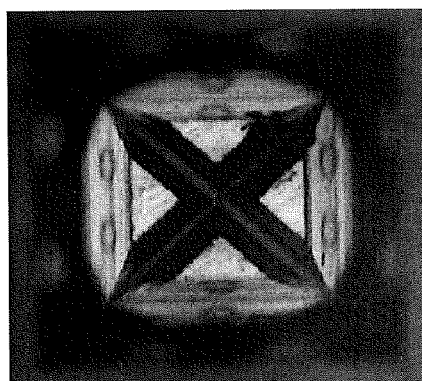


FIG. 13B

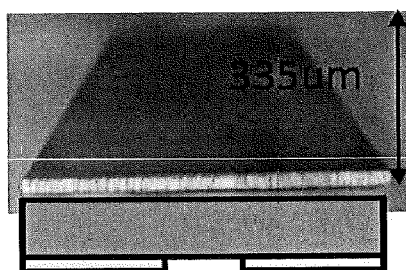
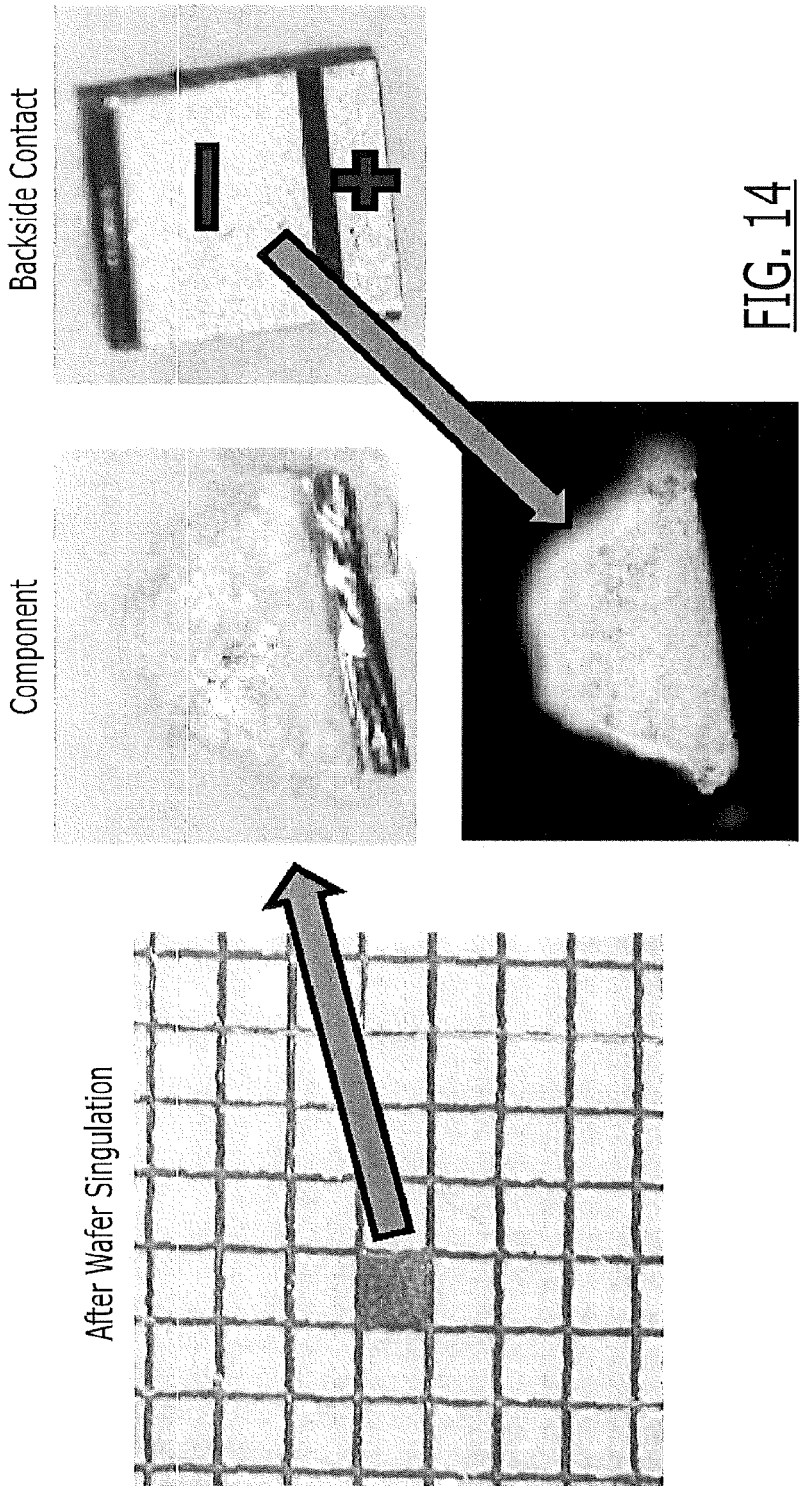
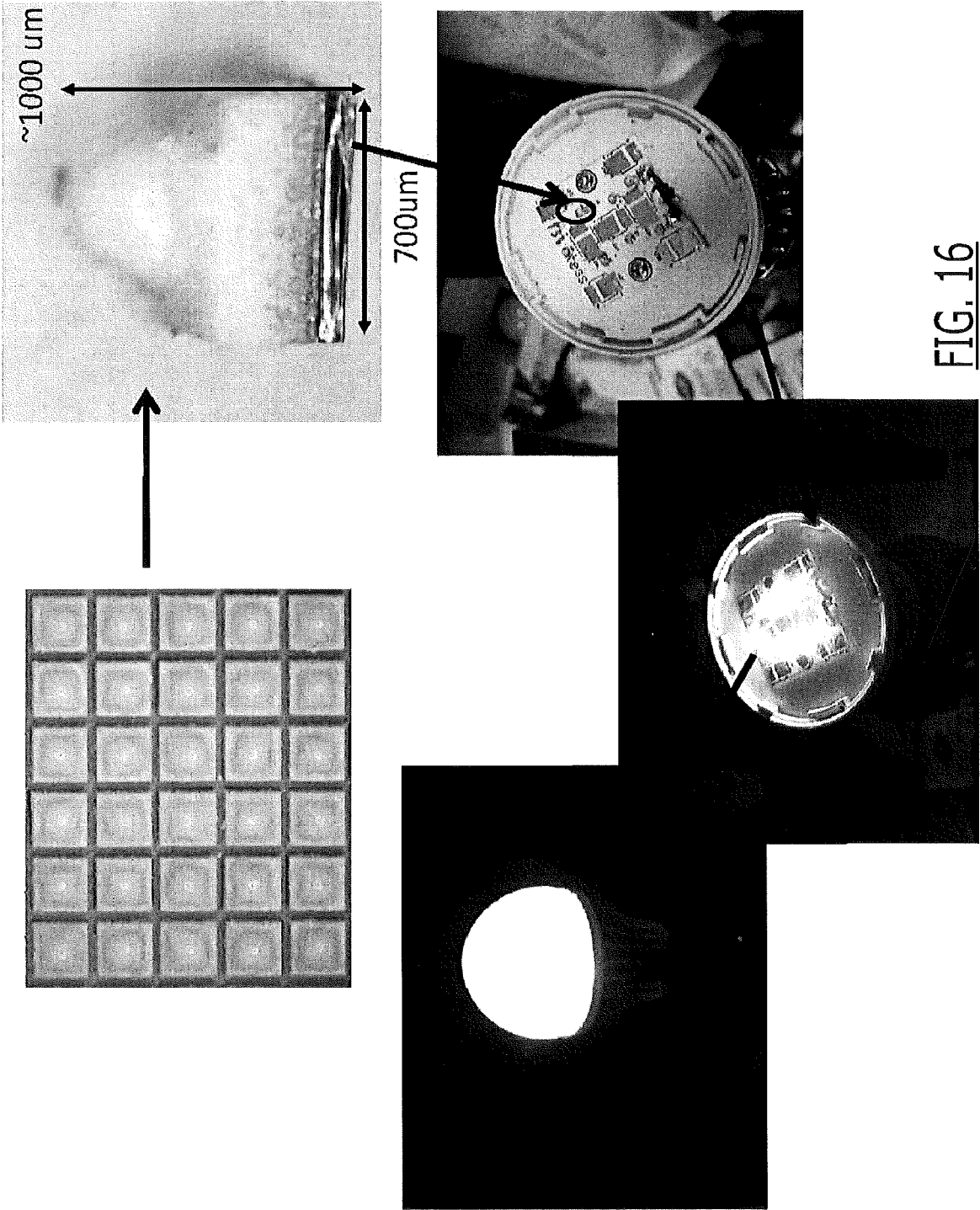


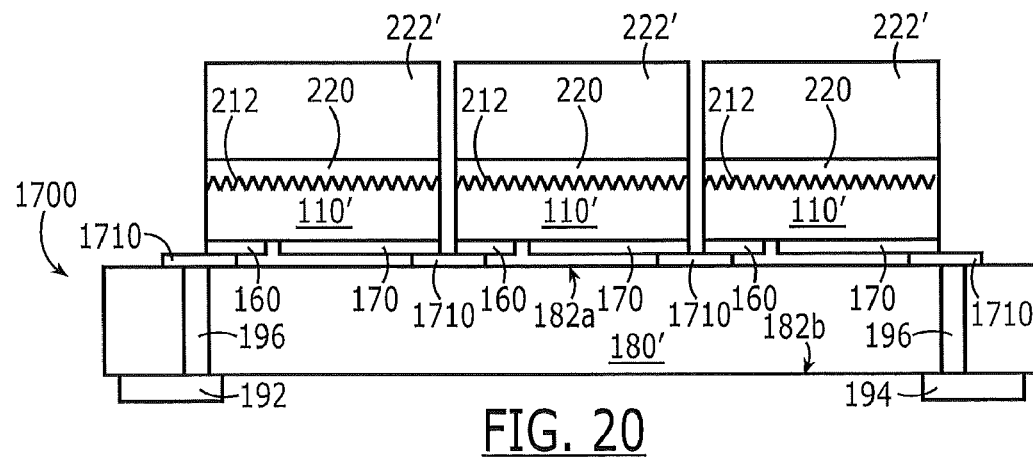
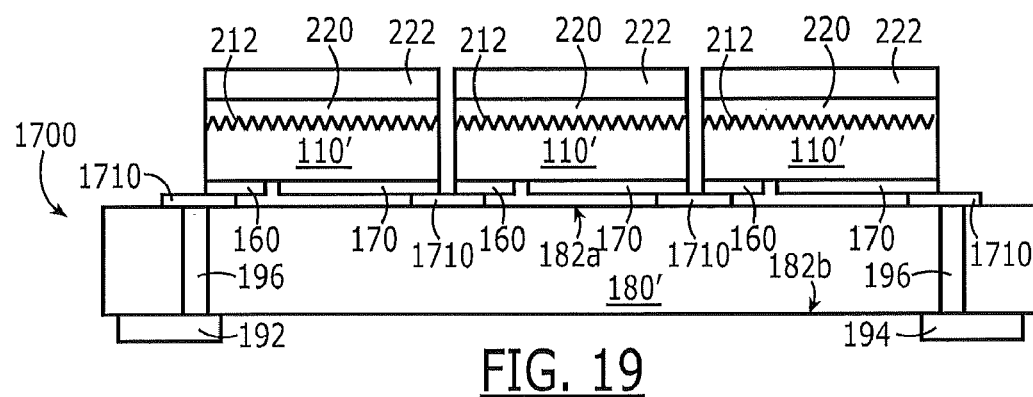
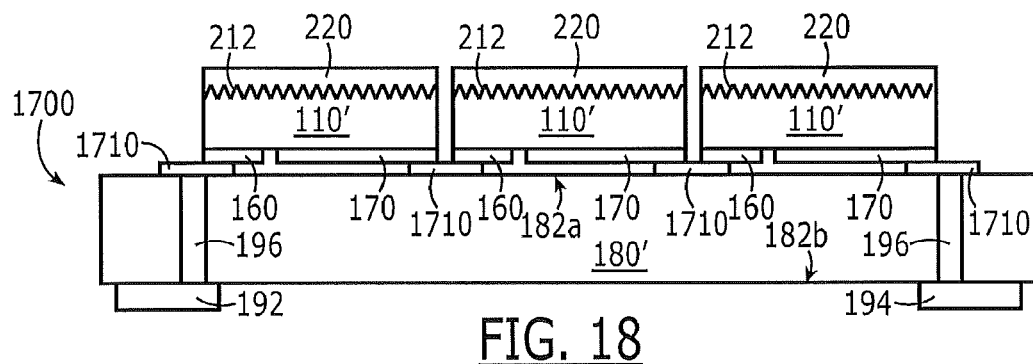
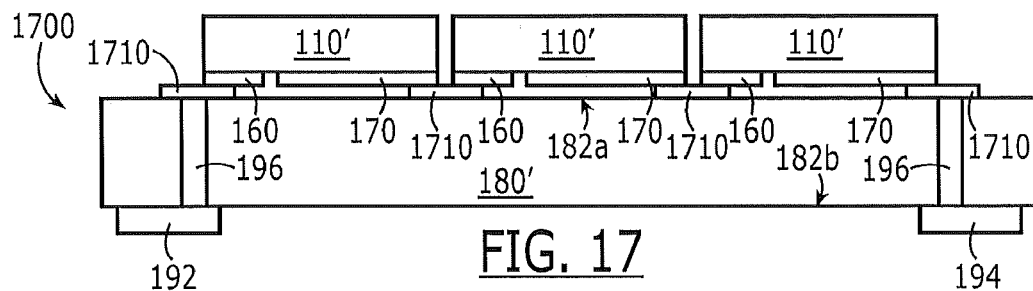
FIG. 13C

Carrier ~100um









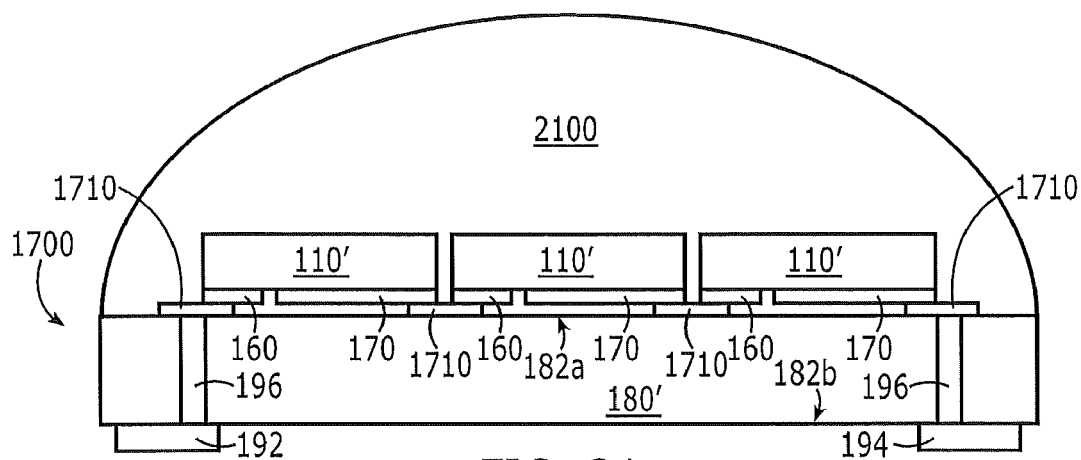


FIG. 21

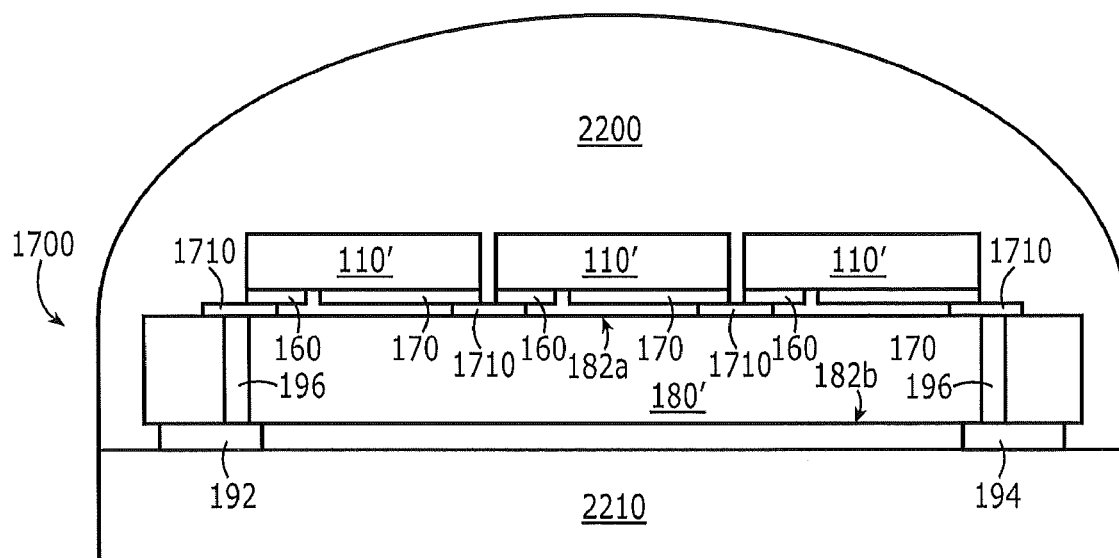


FIG. 22

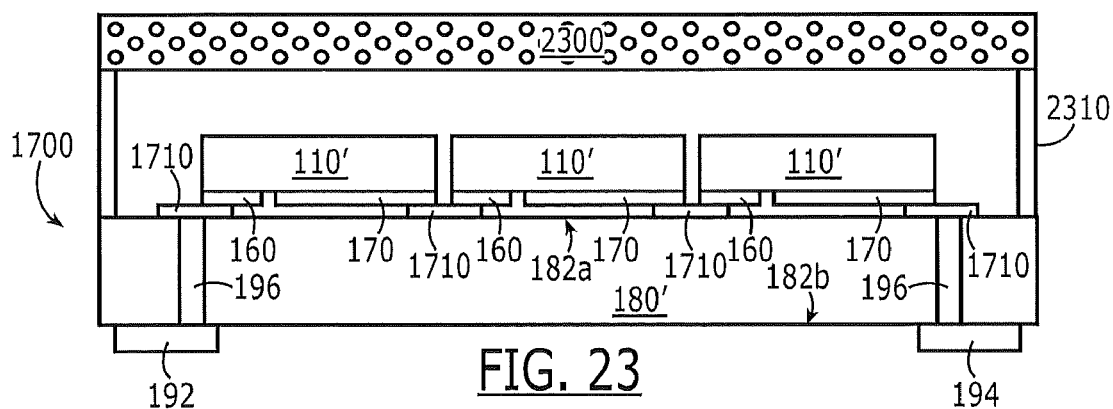


FIG. 23

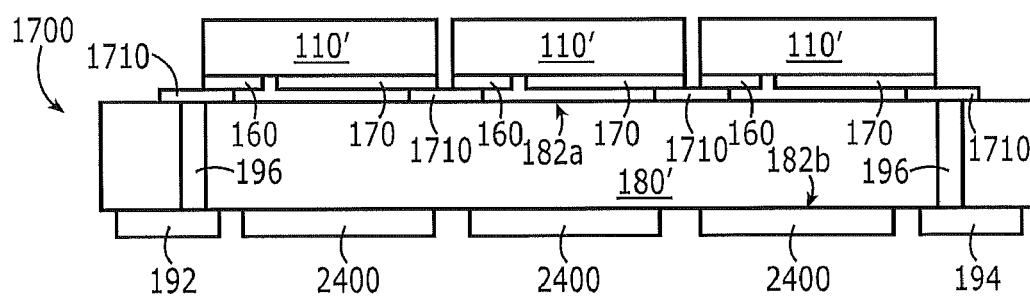


FIG. 24

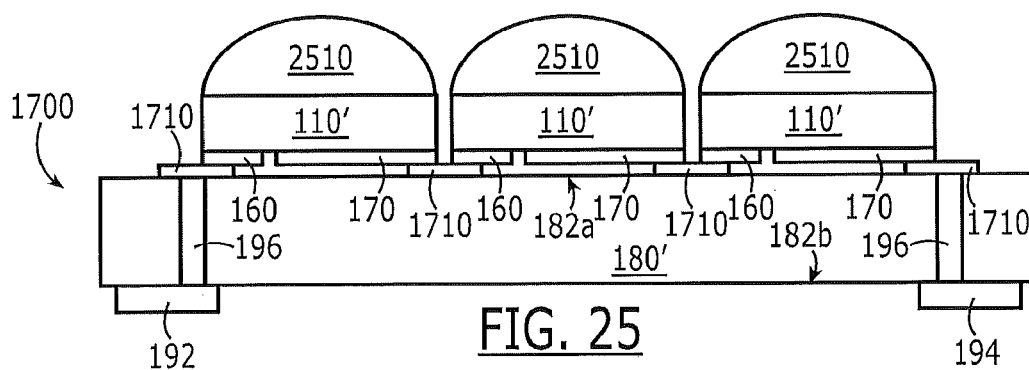


FIG. 25

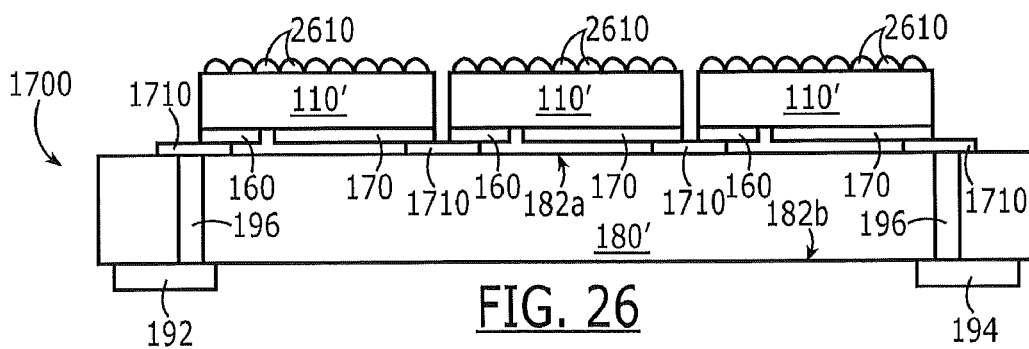
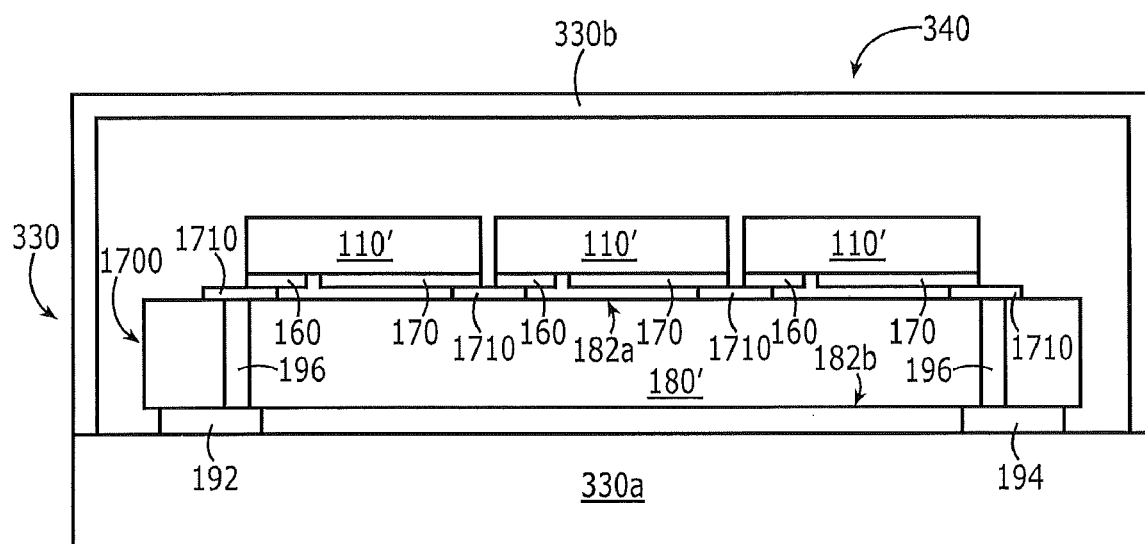


FIG. 26



**FIG. 27**

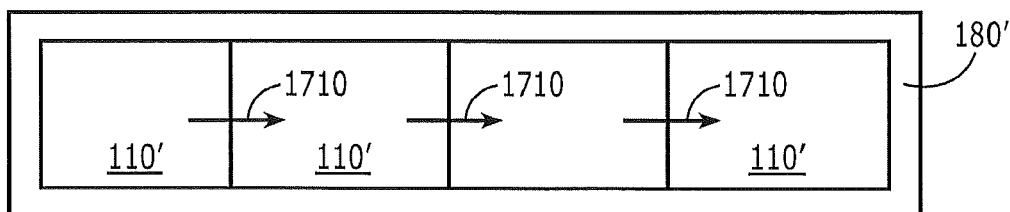


FIG. 28A

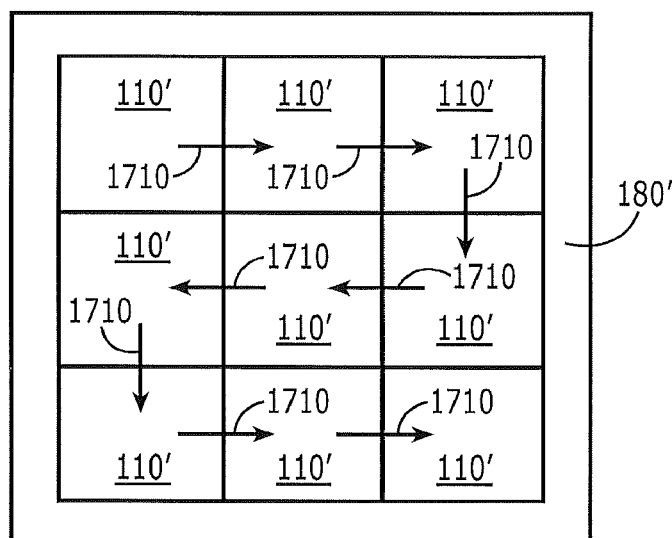


FIG. 28B

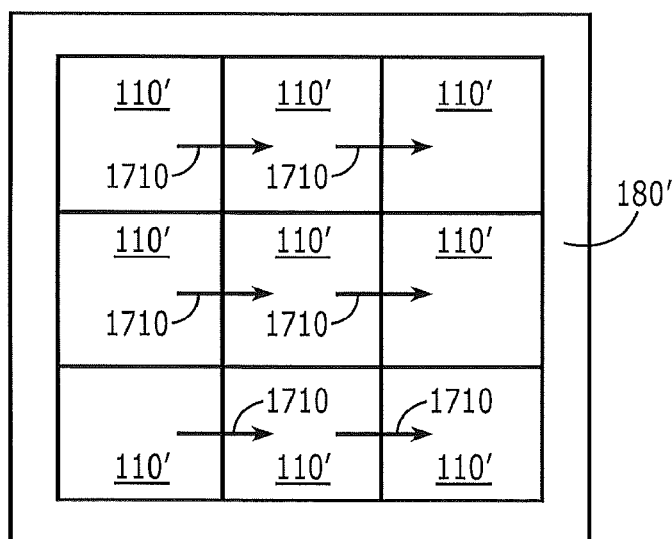


FIG. 28C

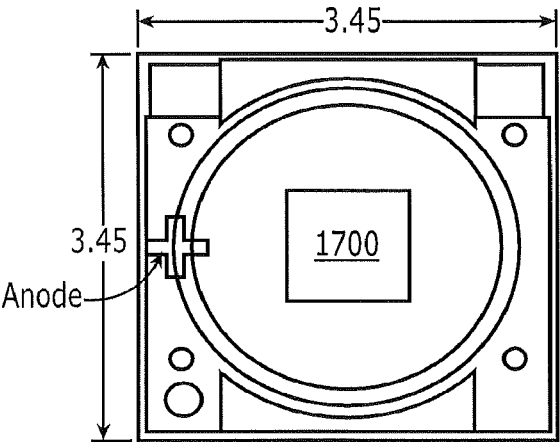


FIG. 29A

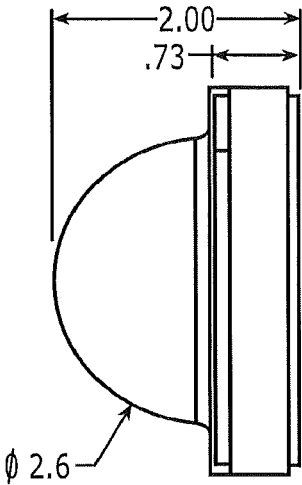


FIG. 29B

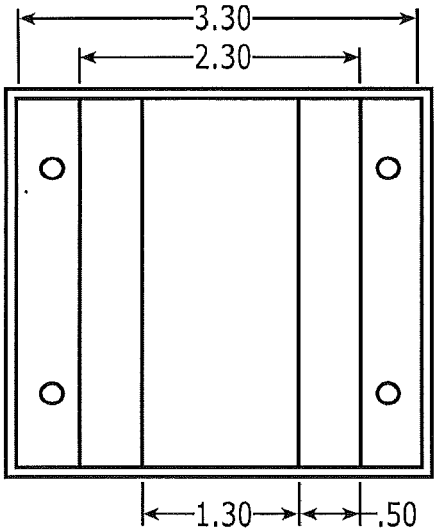
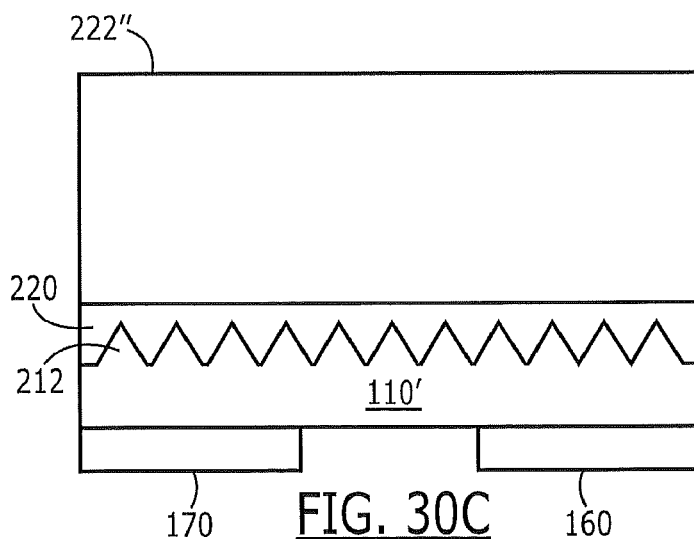
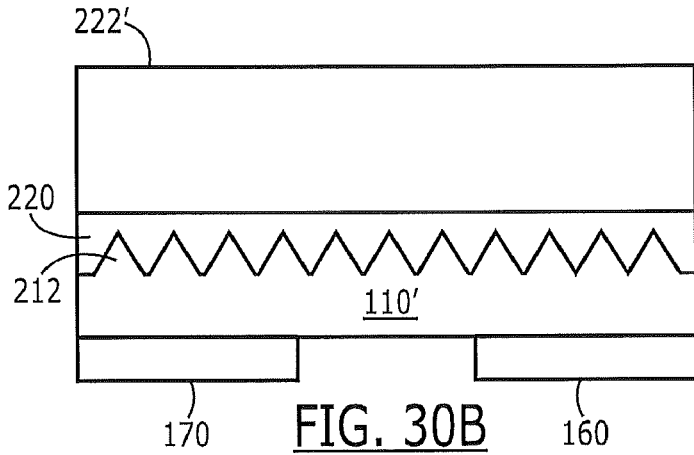
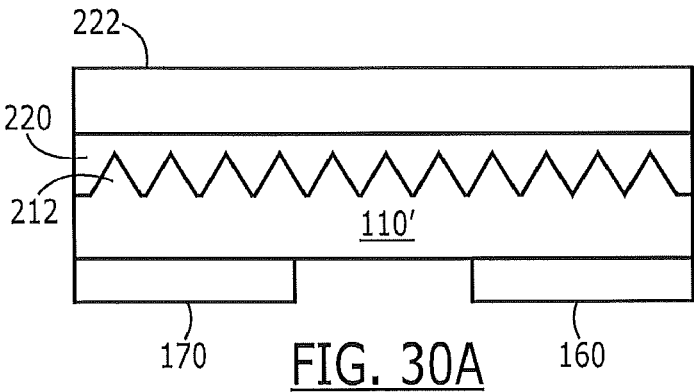


FIG. 29C





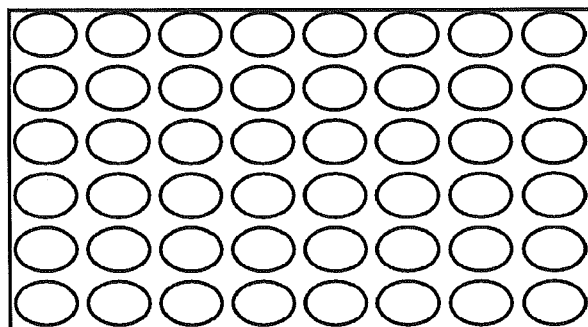


FIG. 31

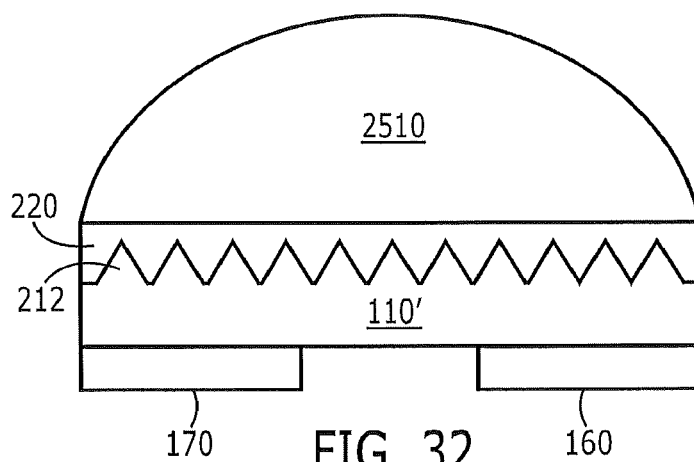
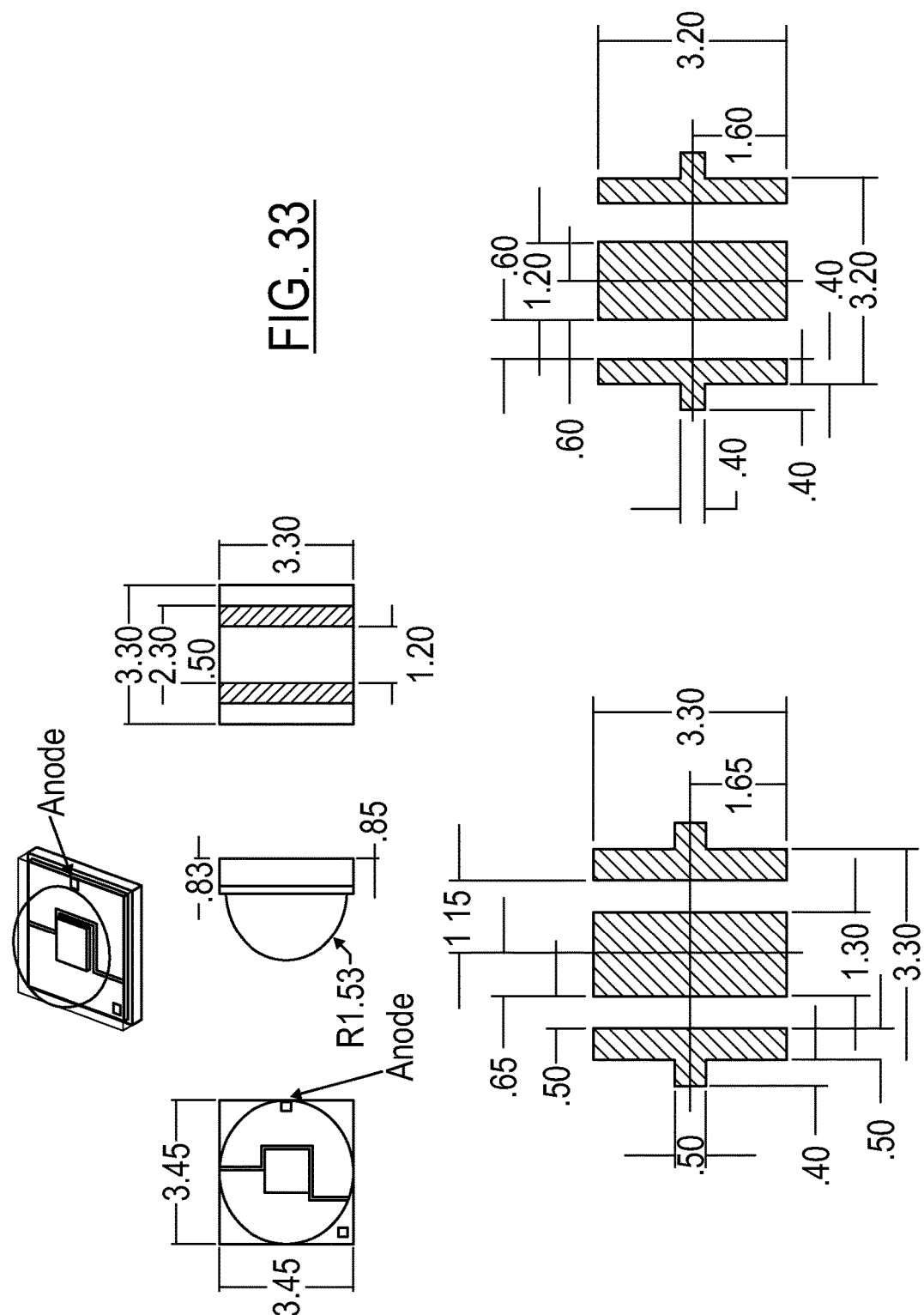


FIG. 32



RECOMMENDED STENCIL PATTERN  
(HATCHED AREA IS OPENING)

RECOMMENDED PCB SOLDER PAD

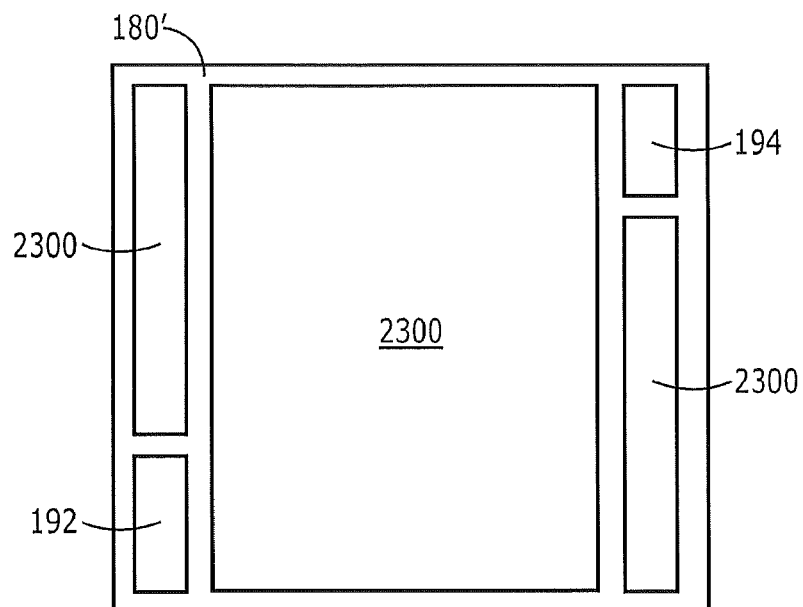


FIG. 34

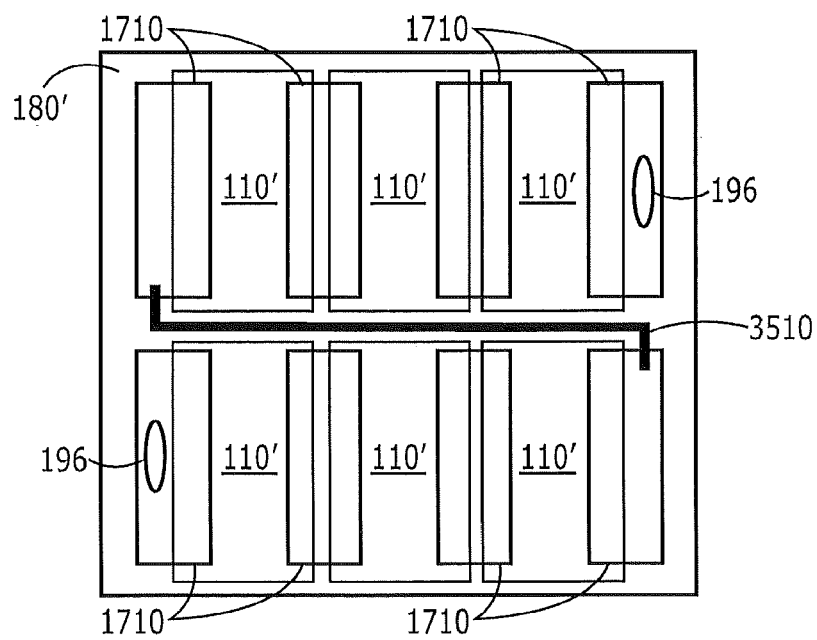


FIG. 35

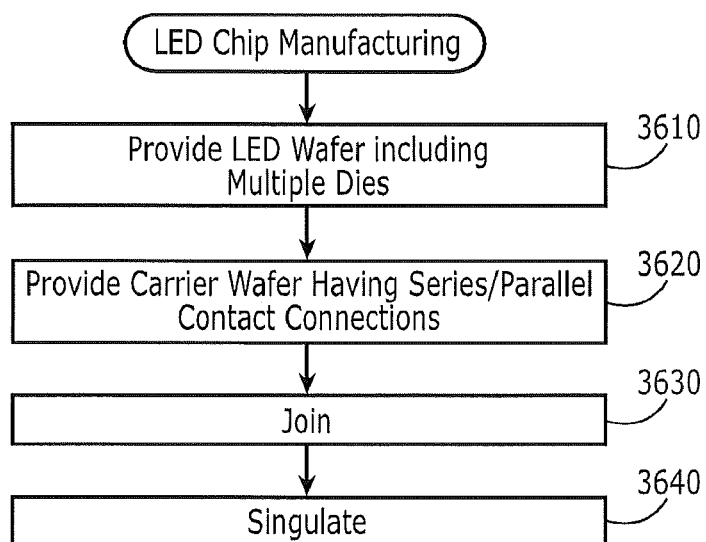


FIG. 36

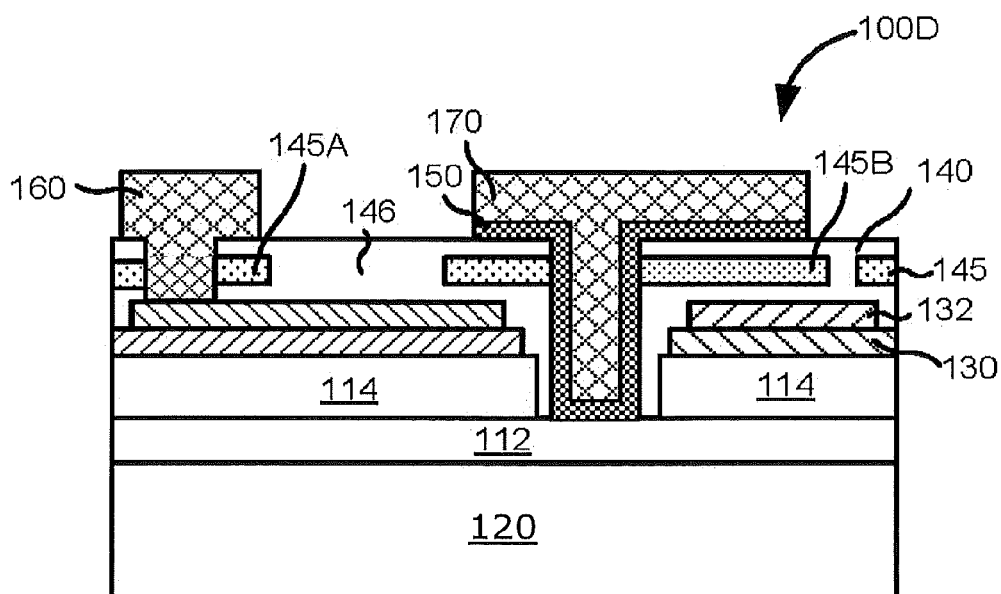
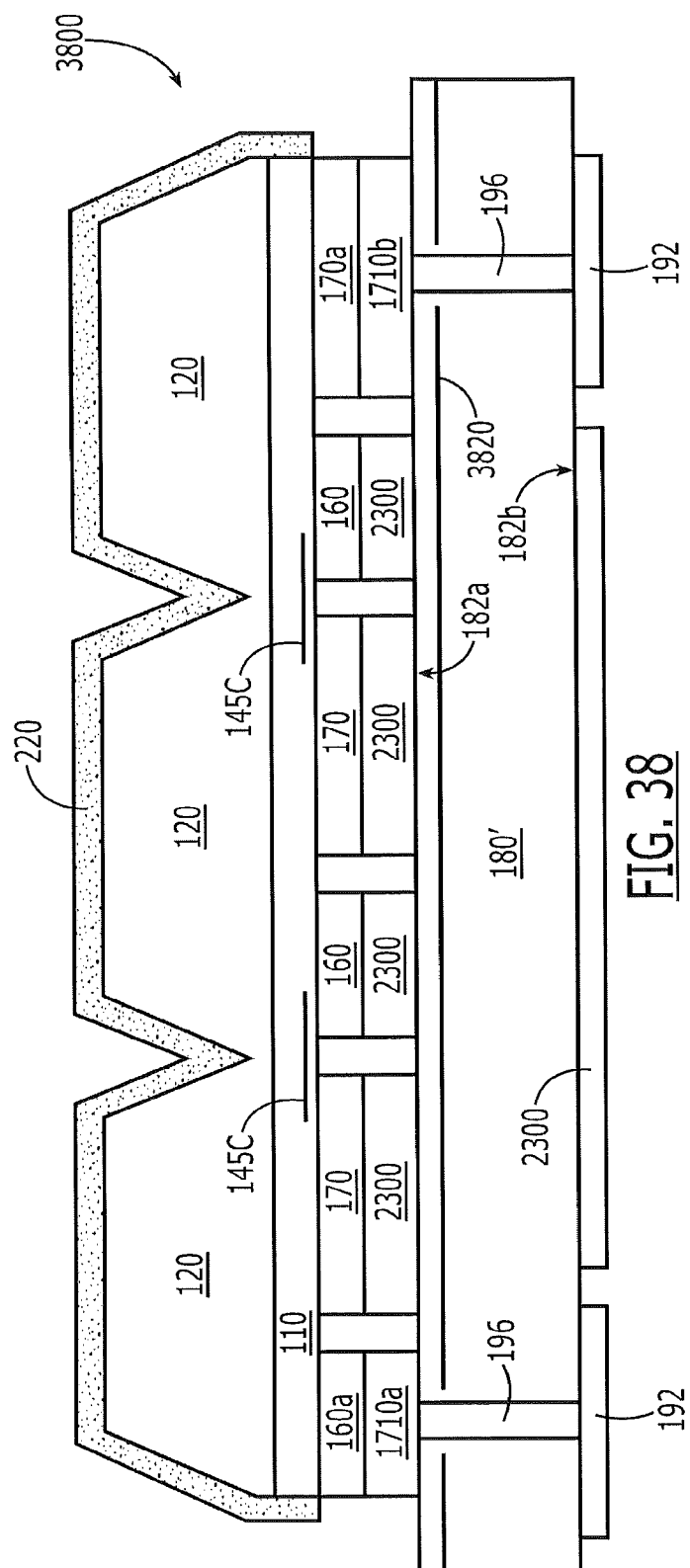
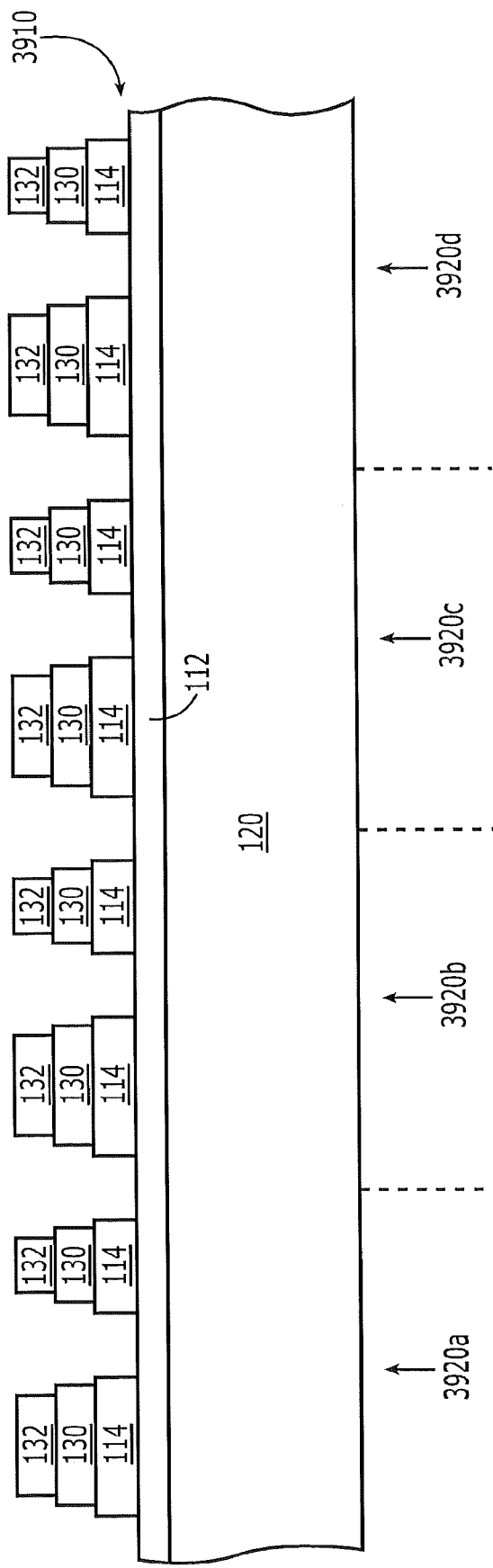
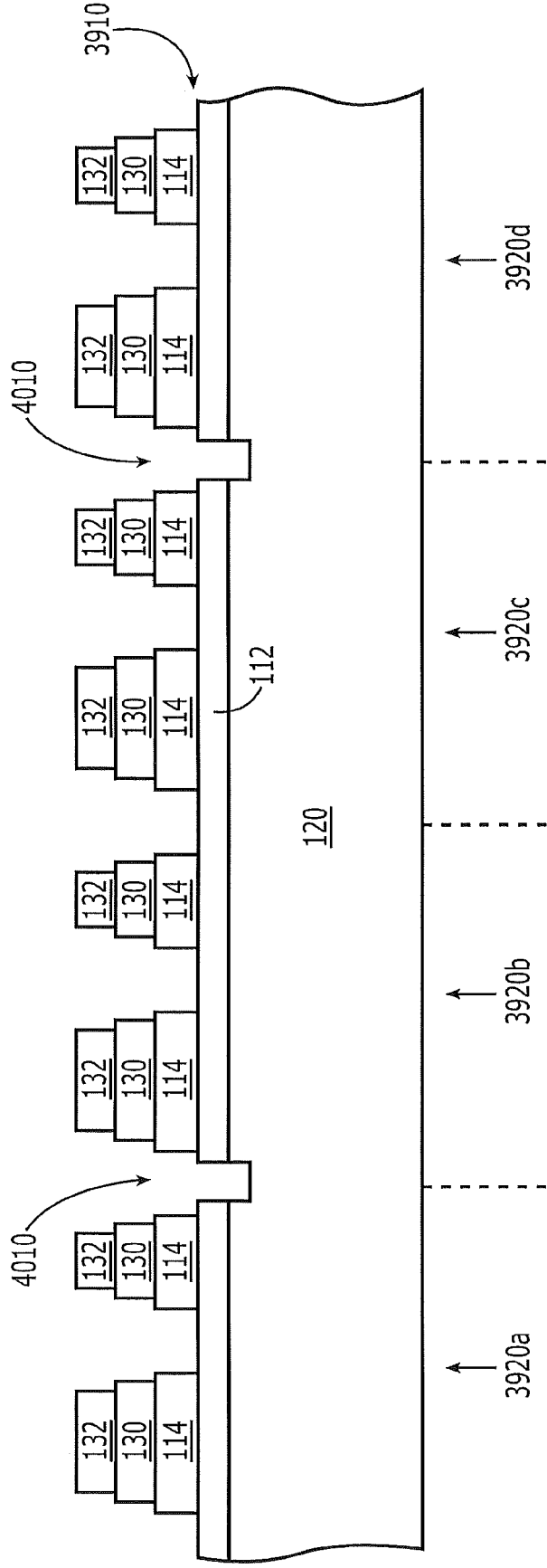


FIG. 37





**FIG. 39**



**FIG. 40**

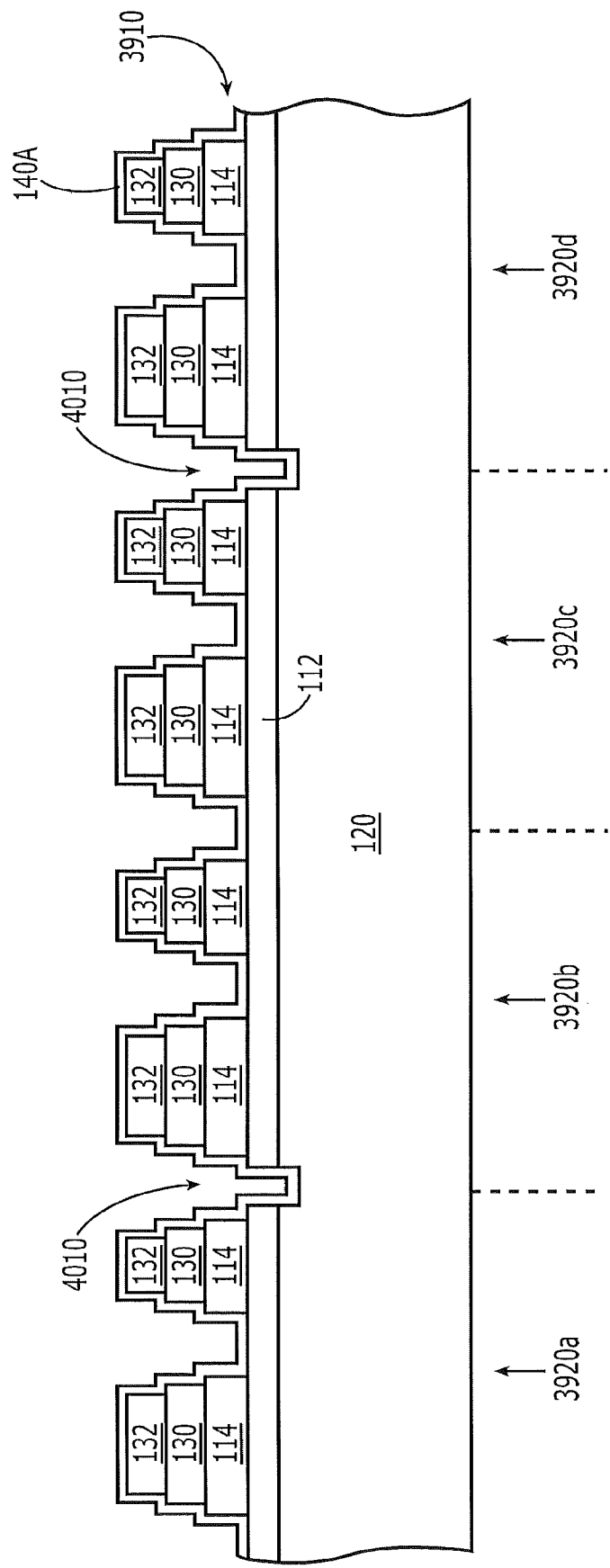


FIG. 41



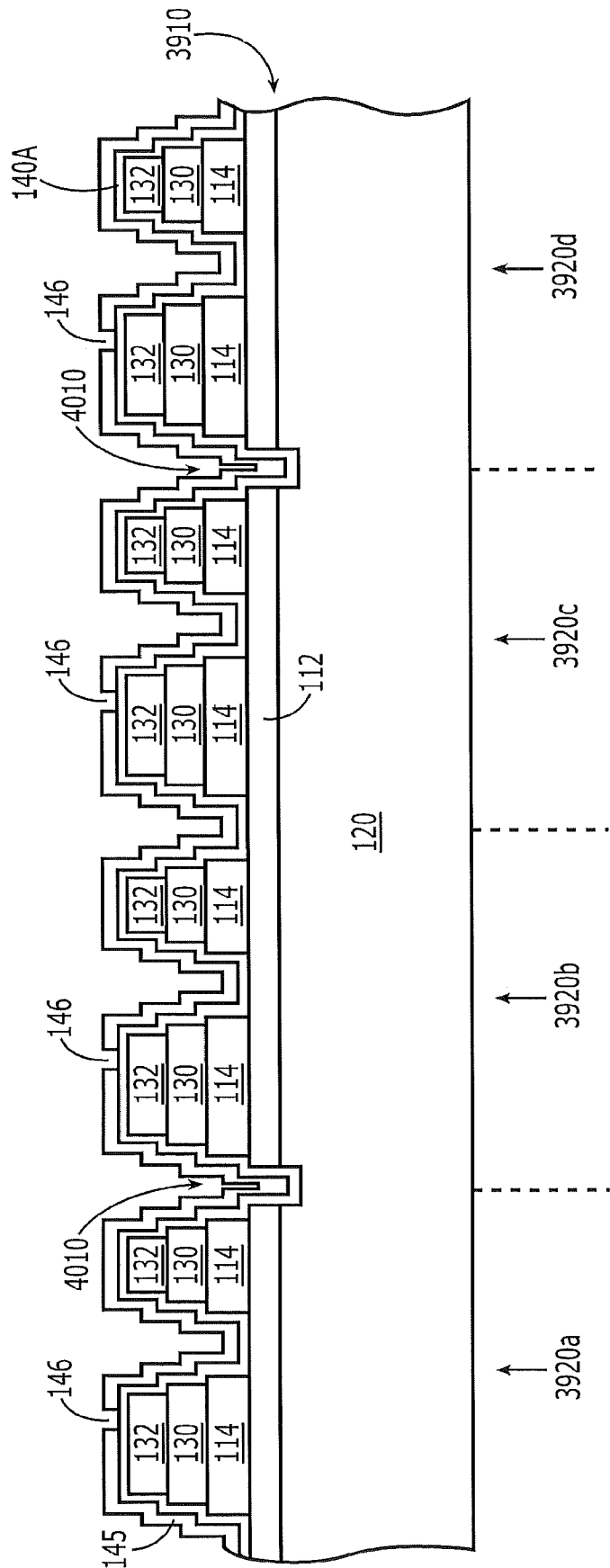


FIG. 42

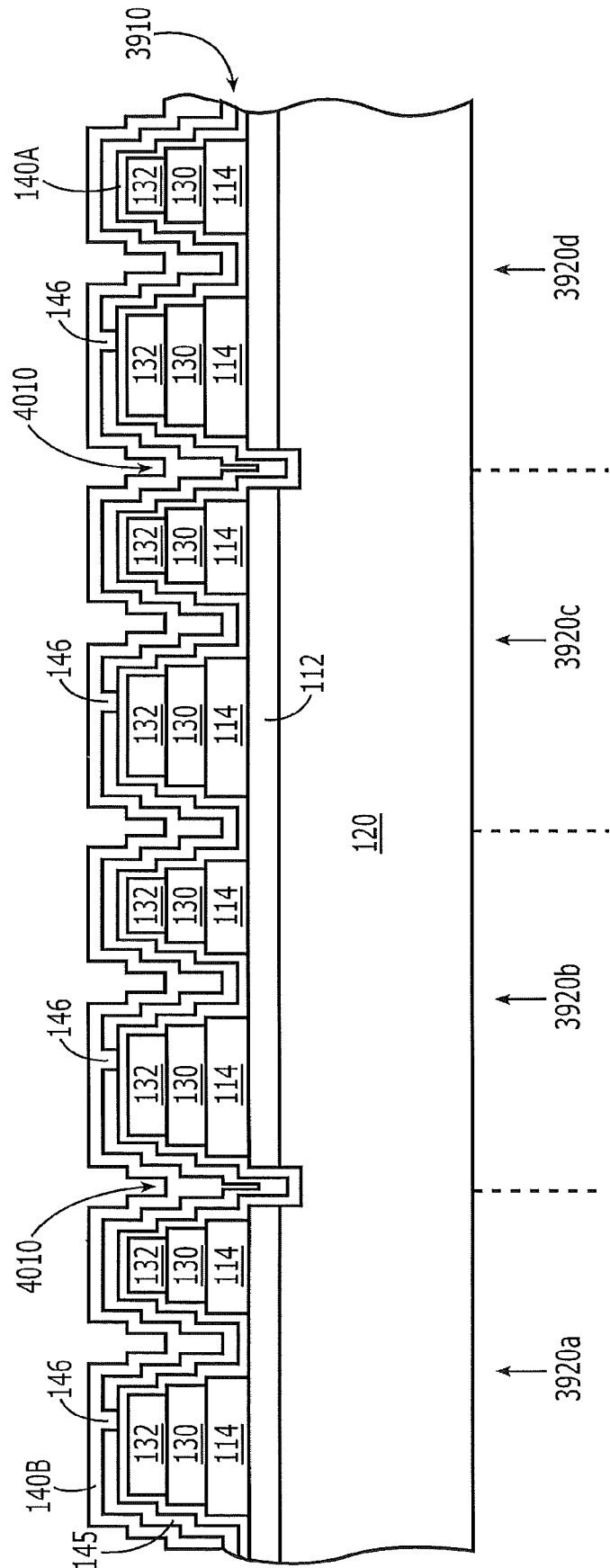
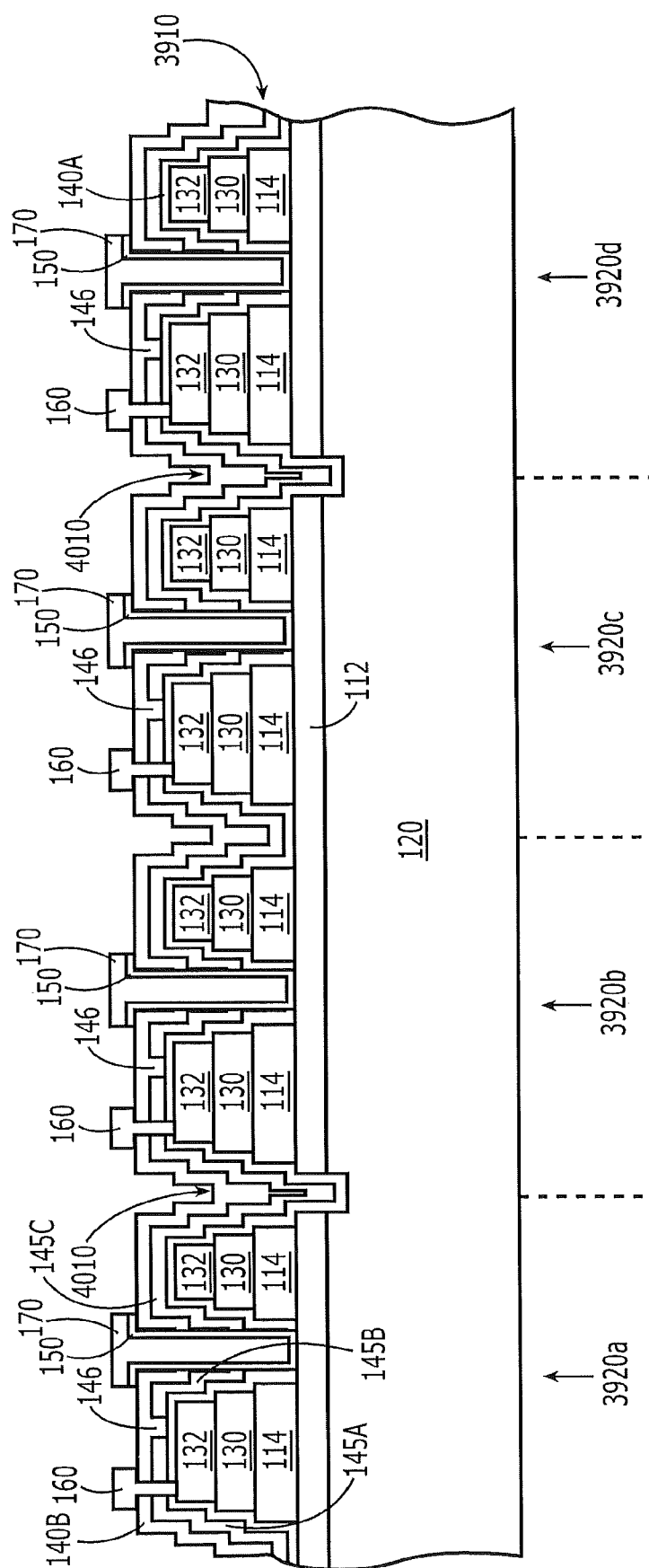


FIG. 43



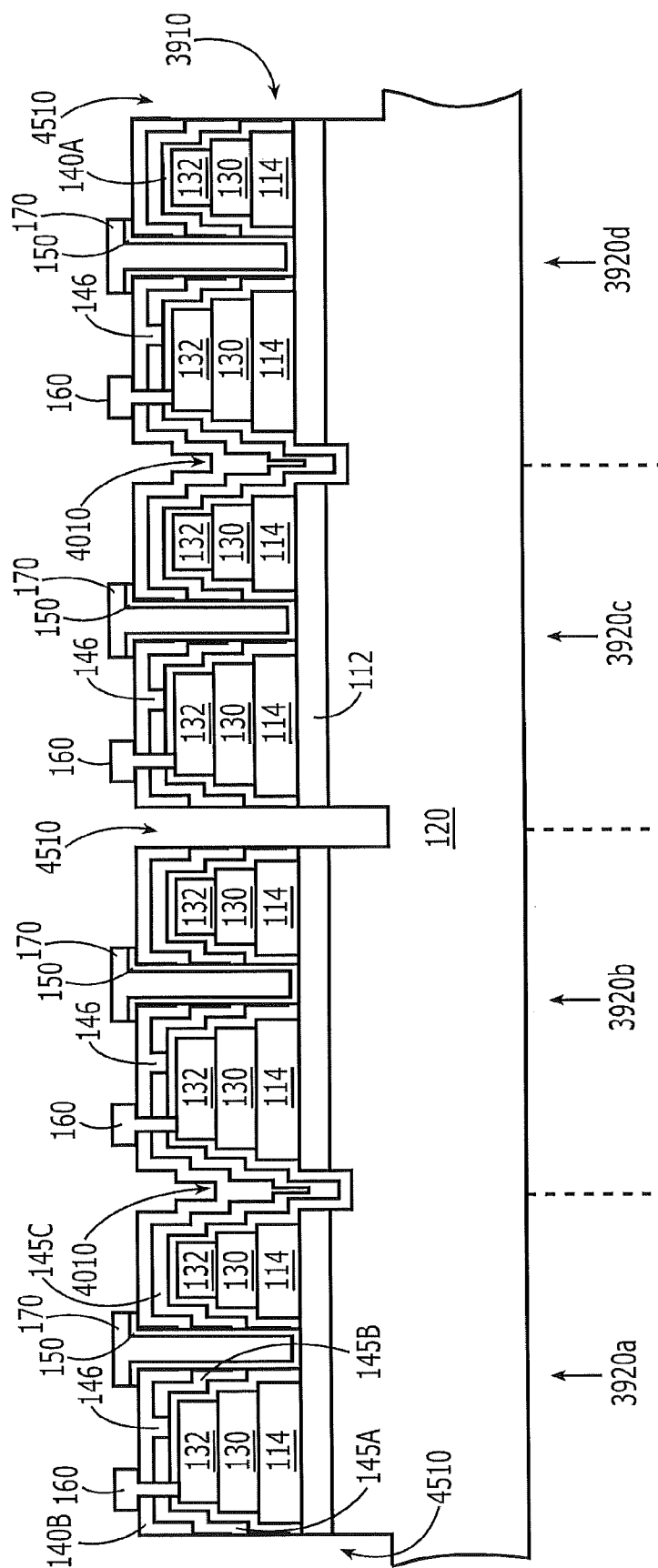


FIG. 45

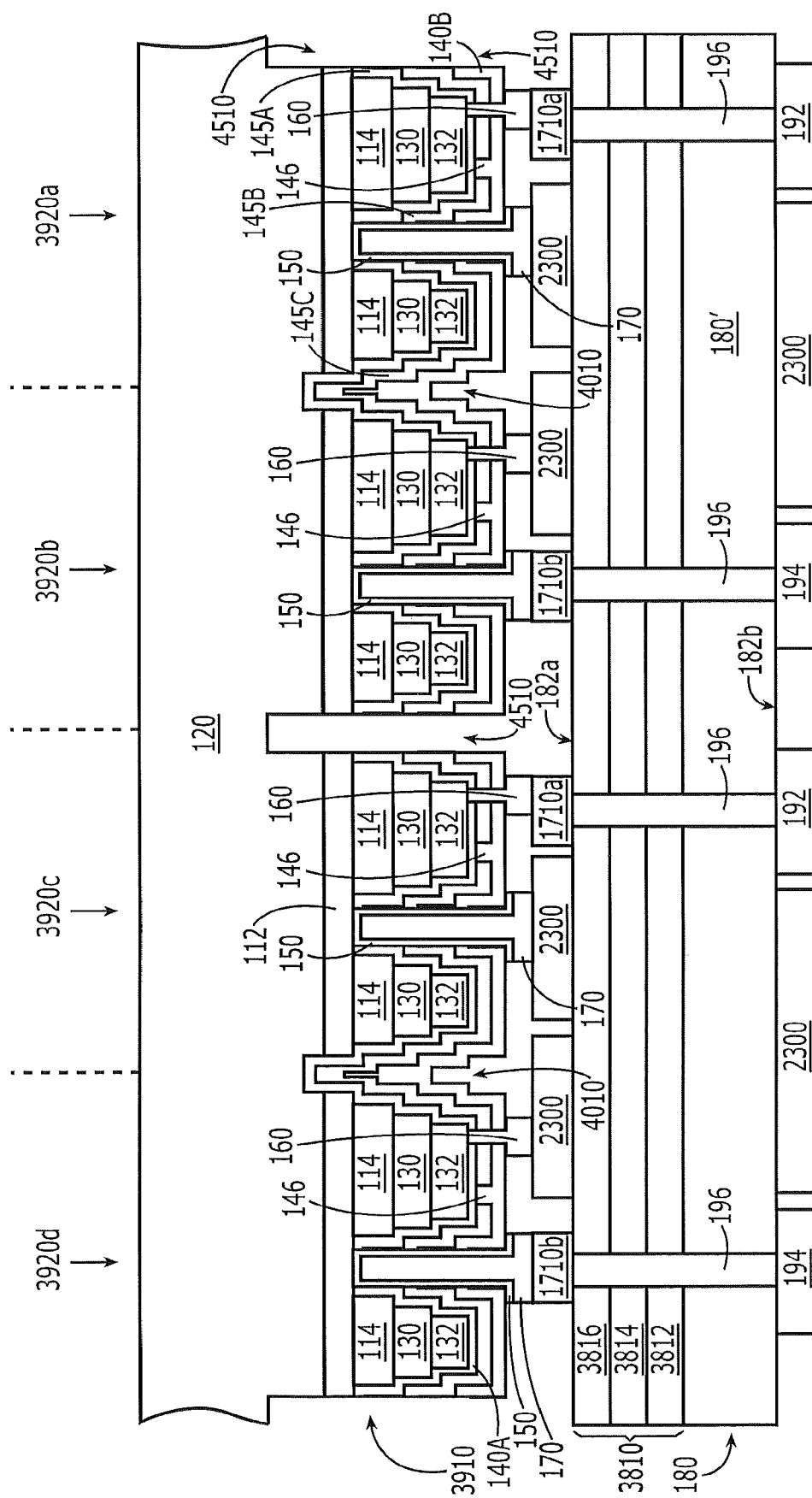


FIG. 46

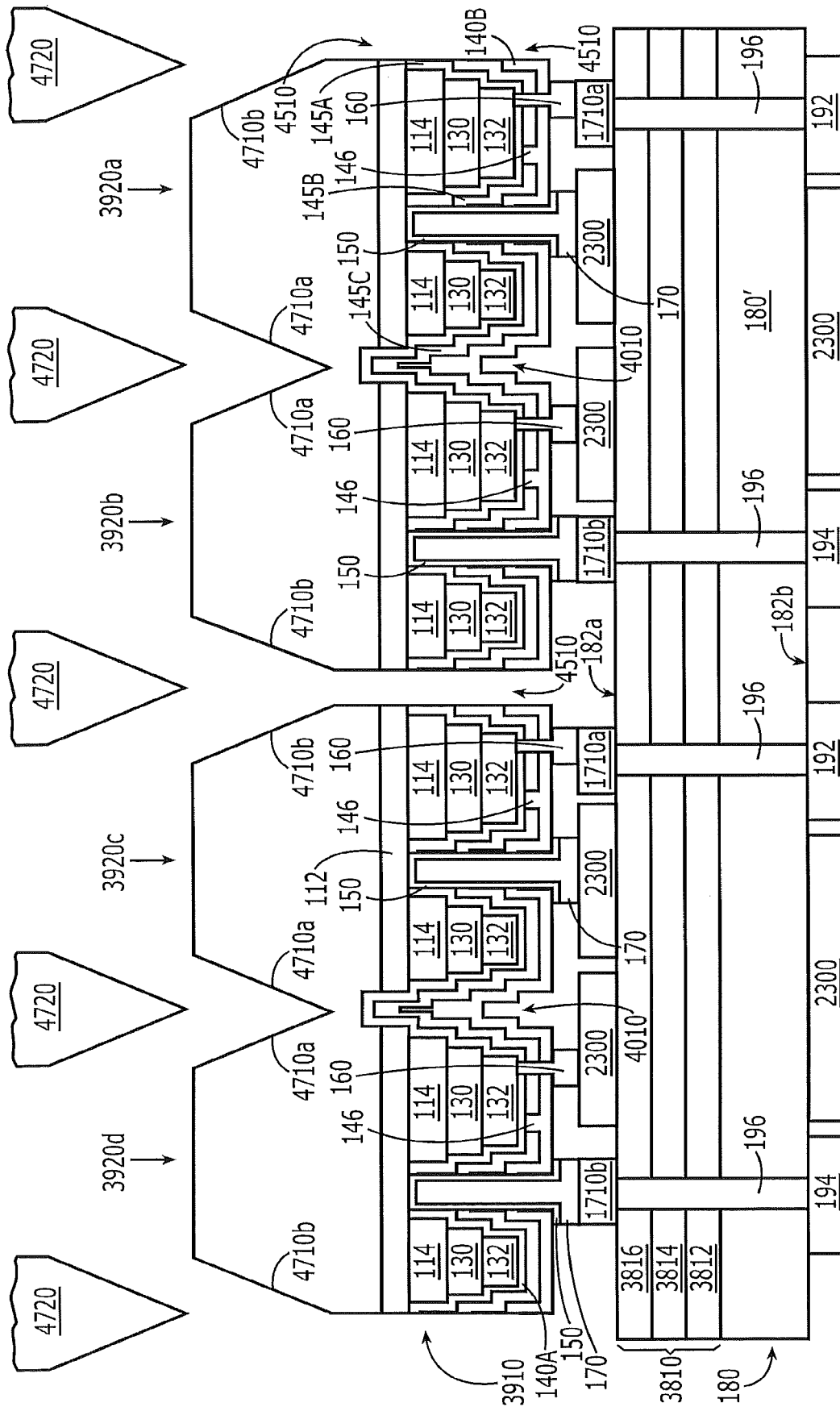


FIG. 47

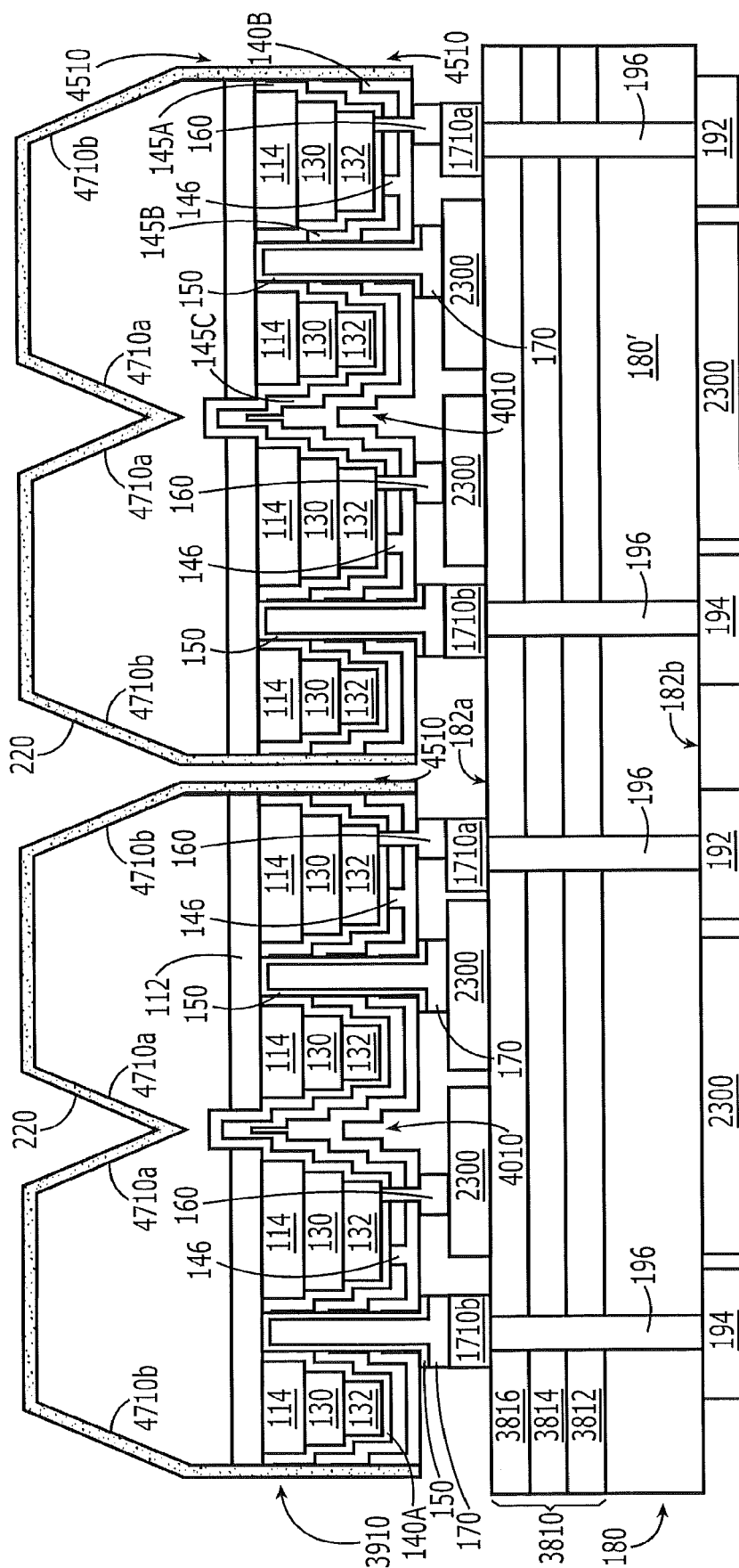
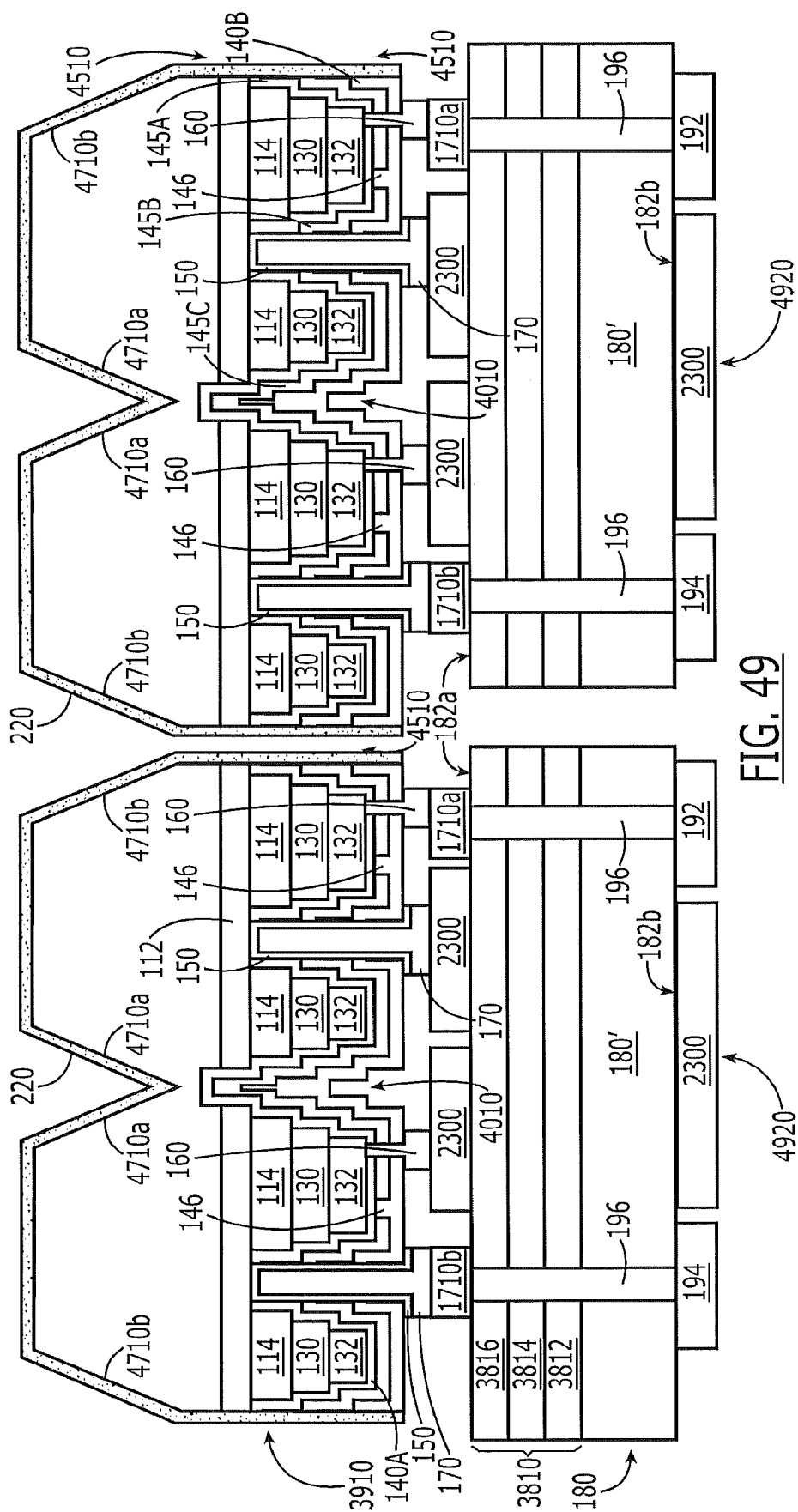


FIG. 48





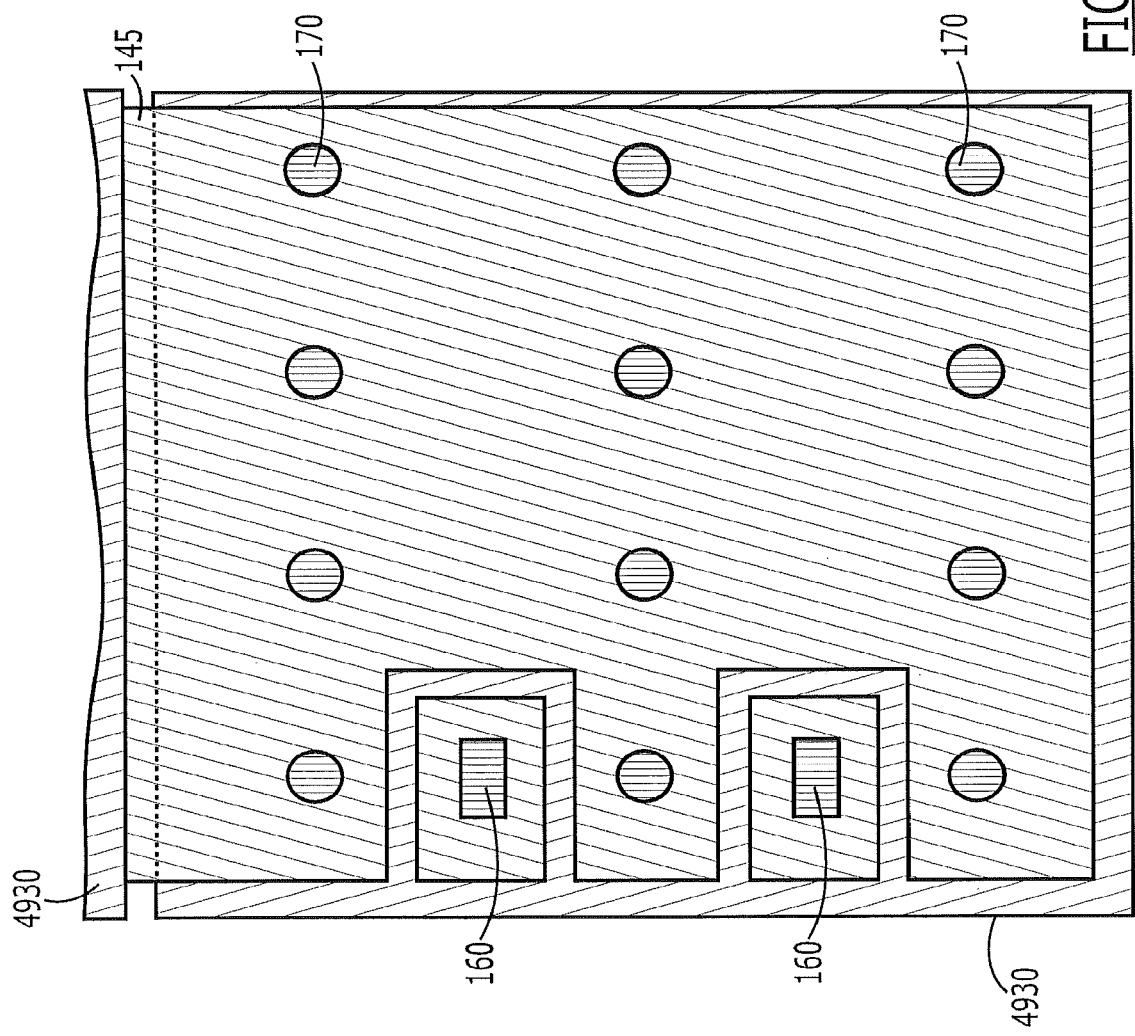
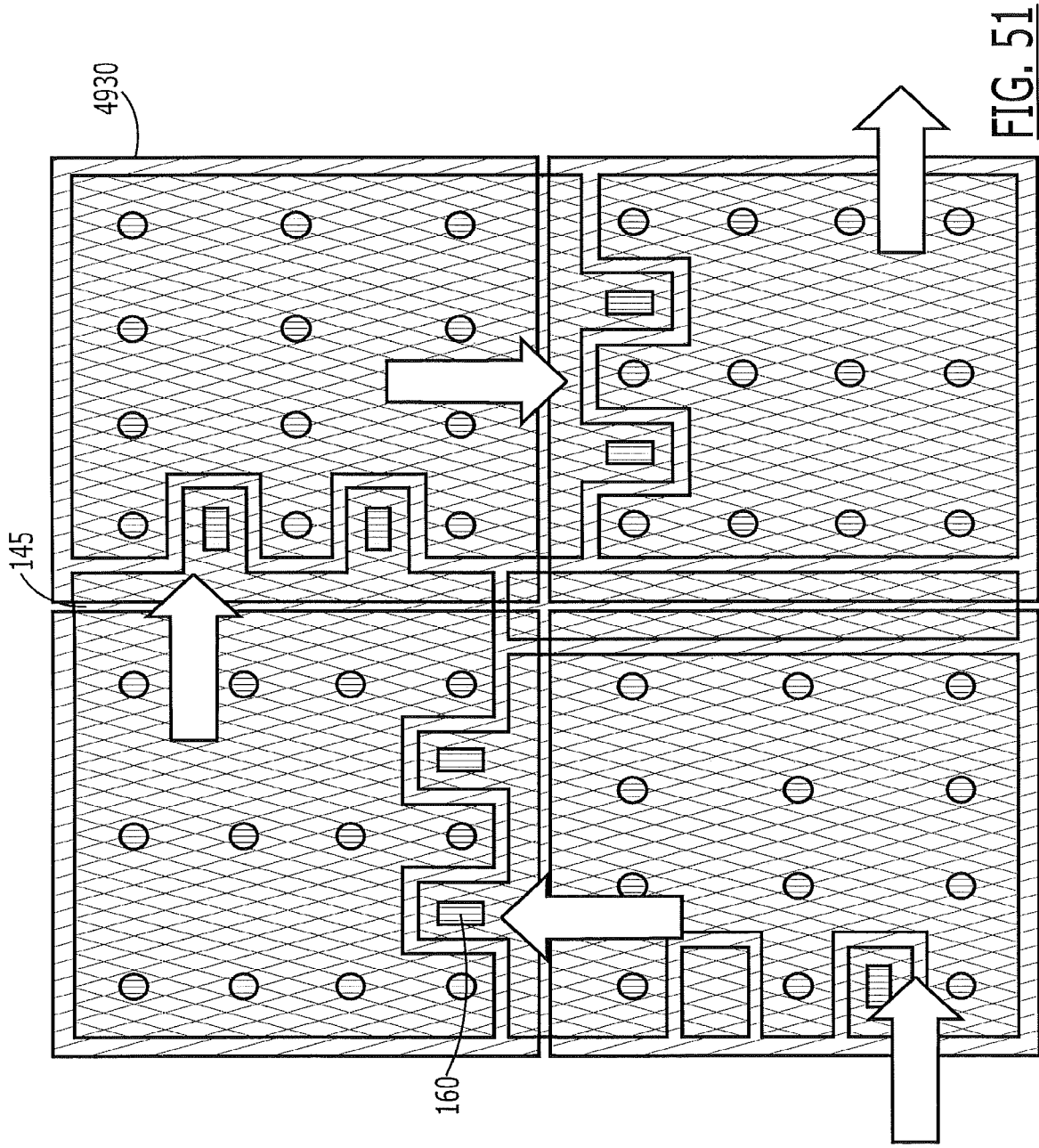
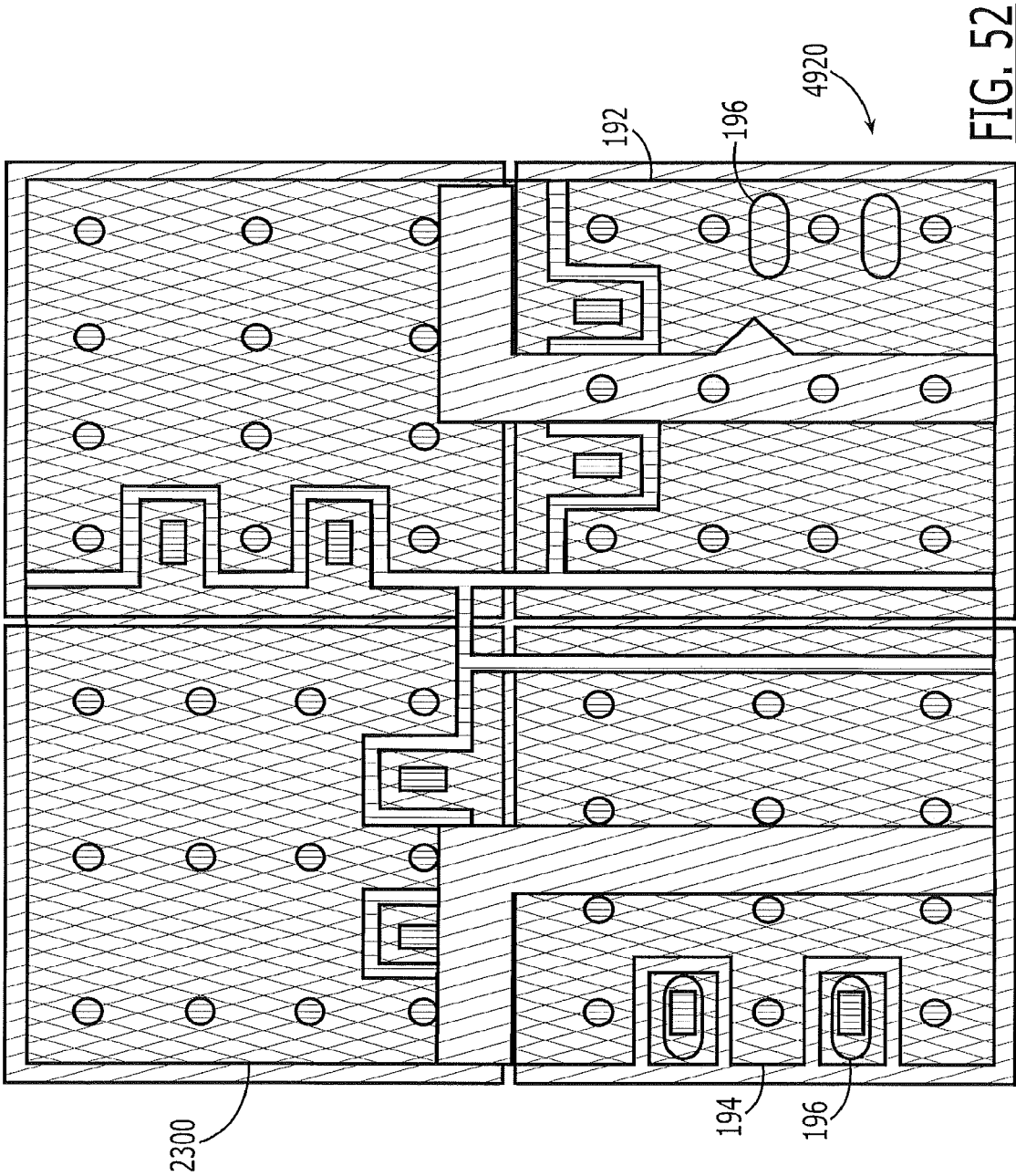
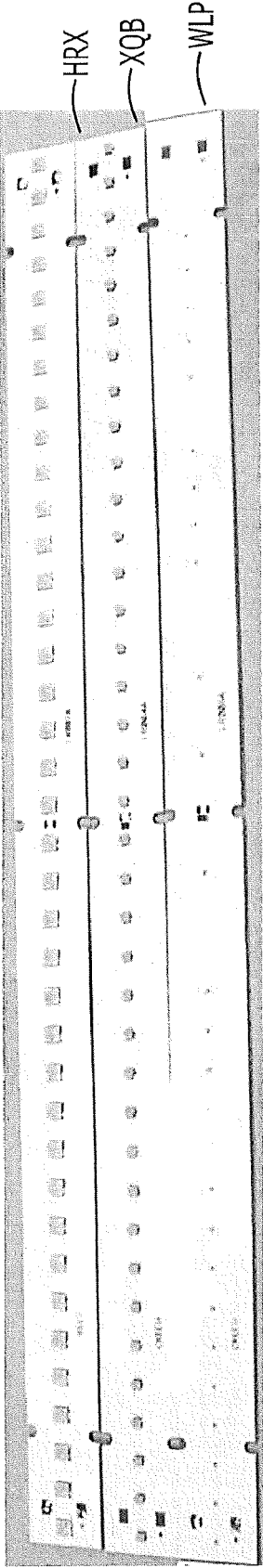


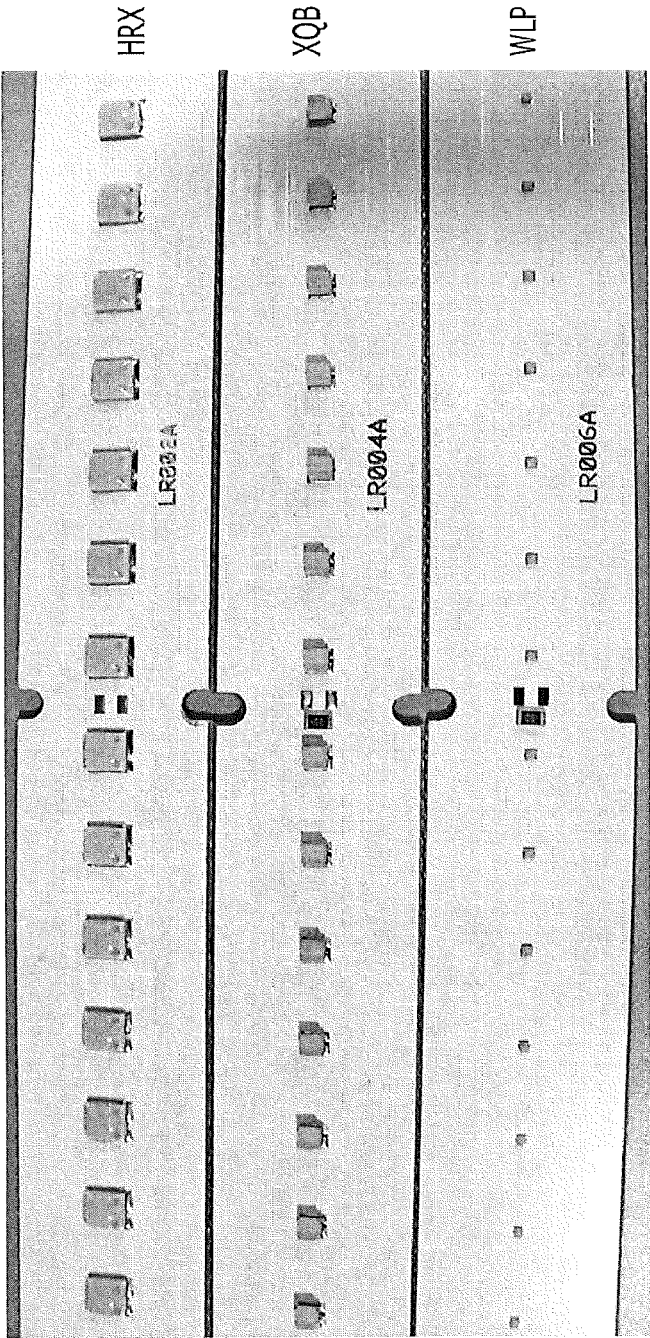
FIG. 50







**FIG. 53A**



**FIG. 53B**

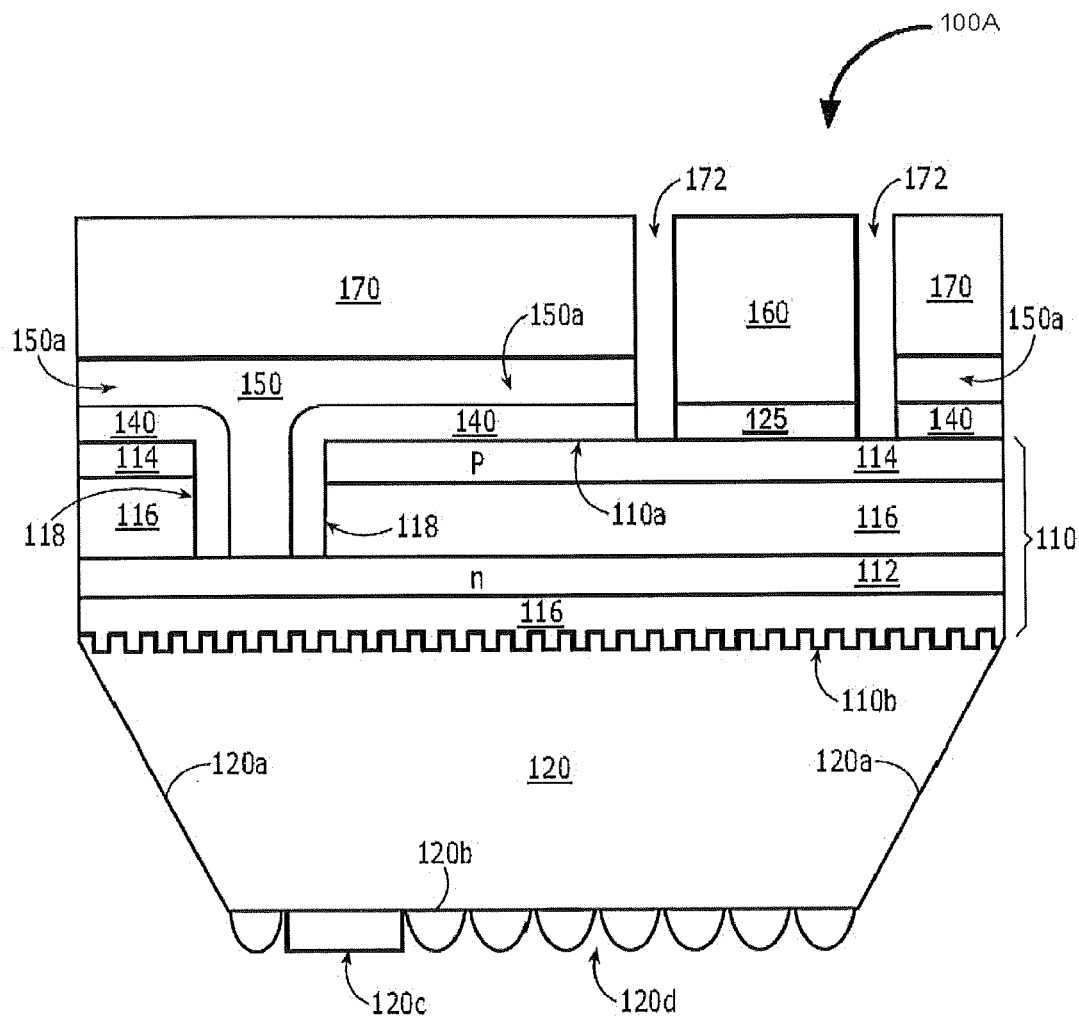


FIG. 54

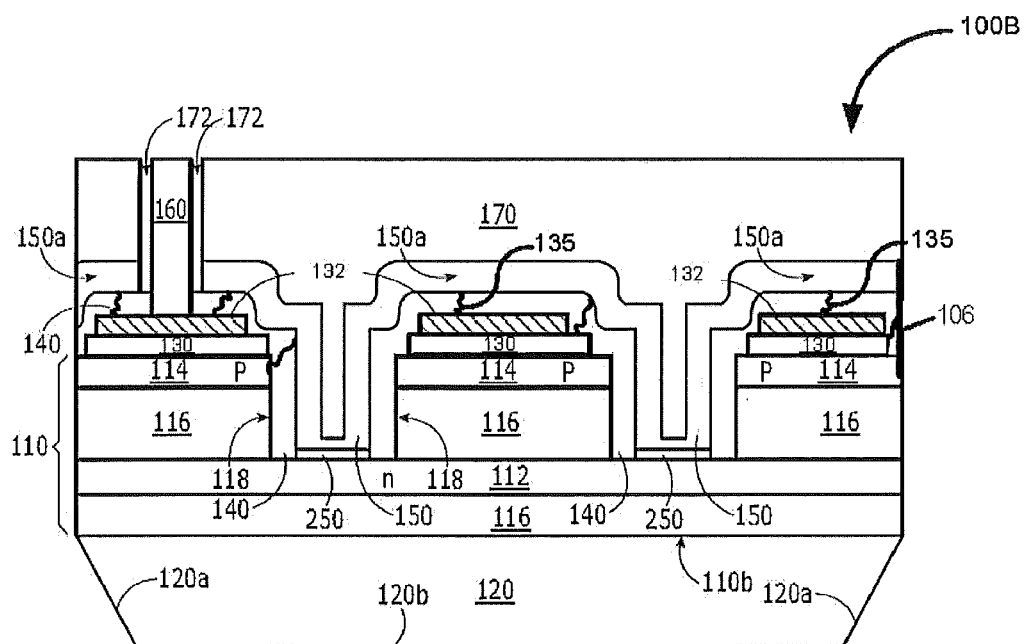


FIG. 55

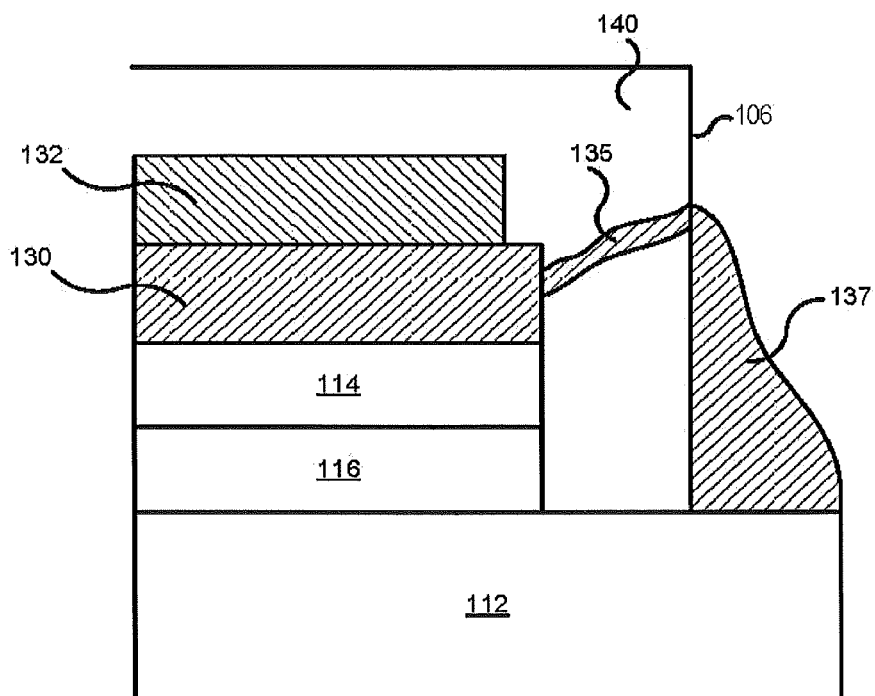
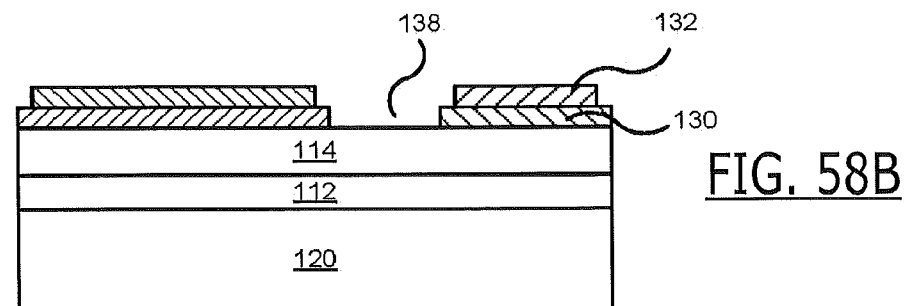
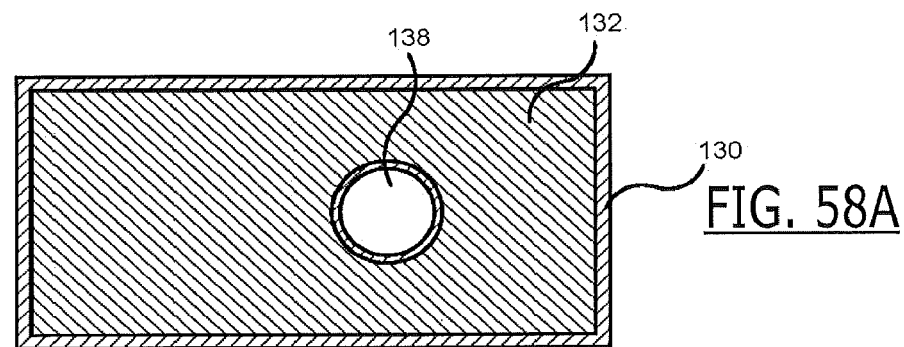
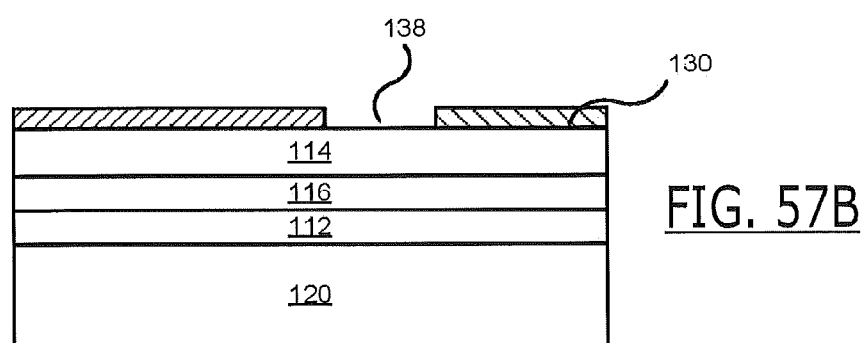
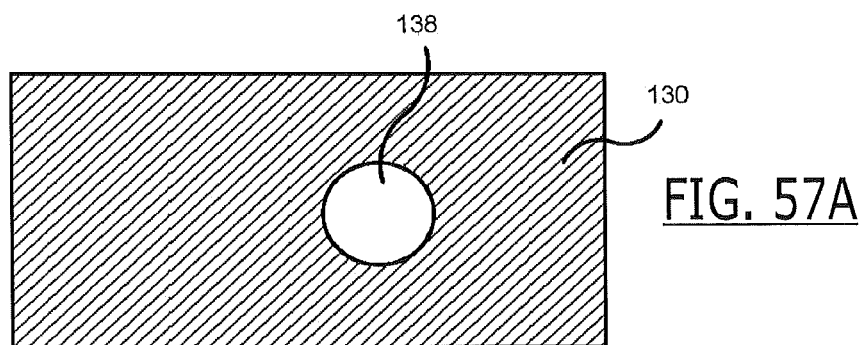
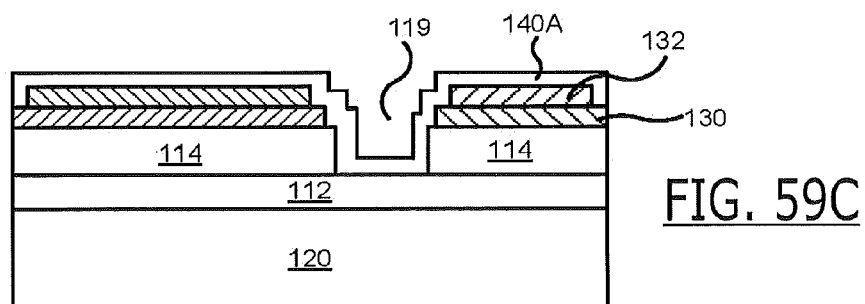
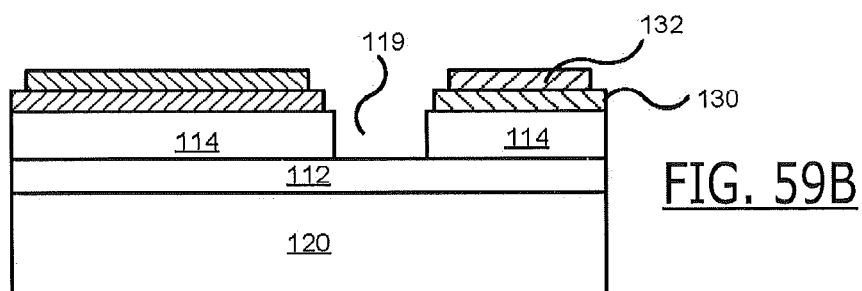
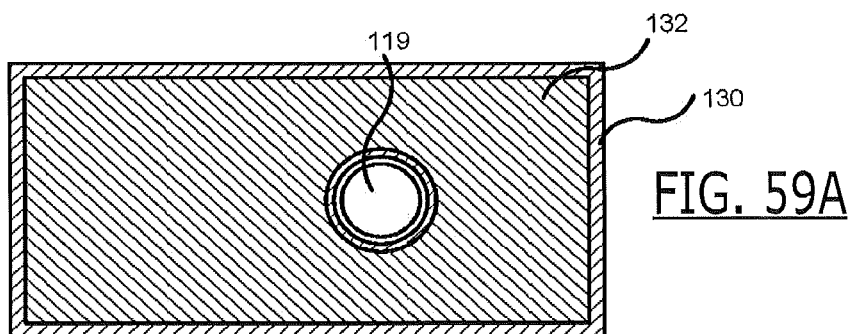
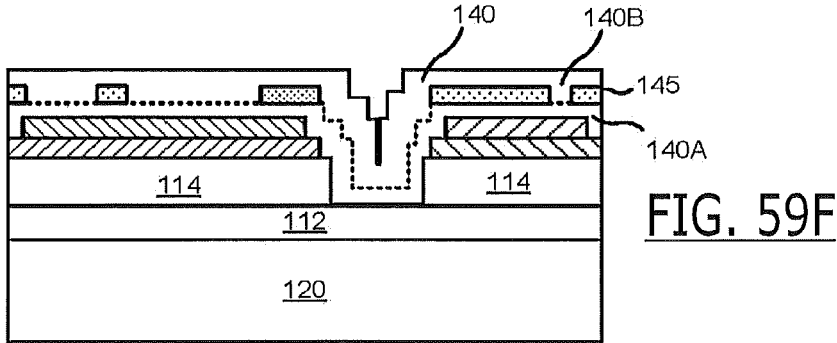
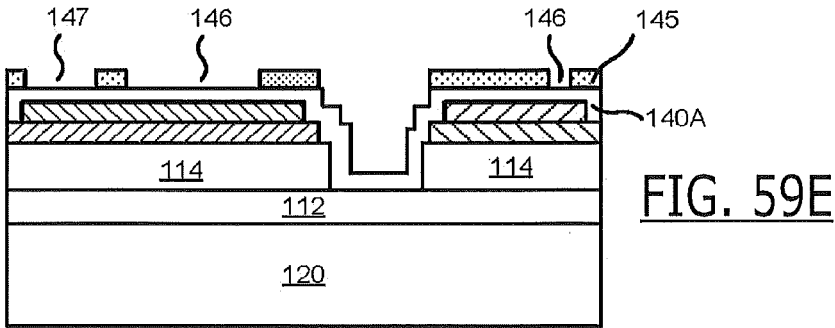
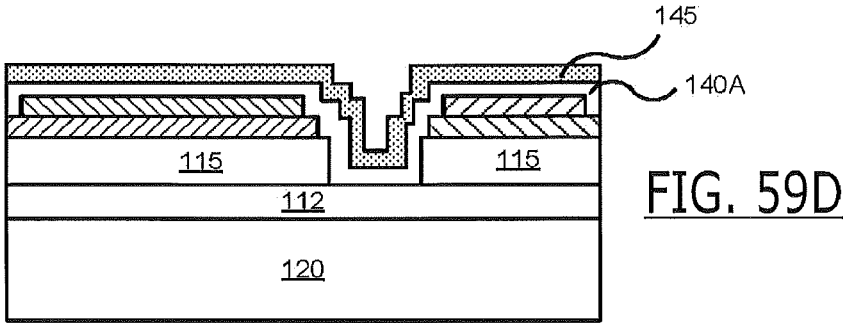


FIG. 56









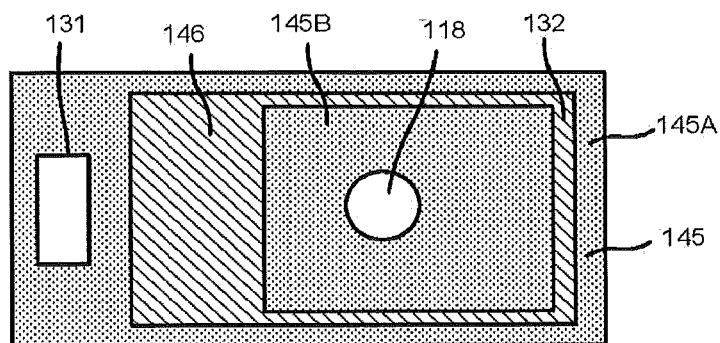


FIG. 60A

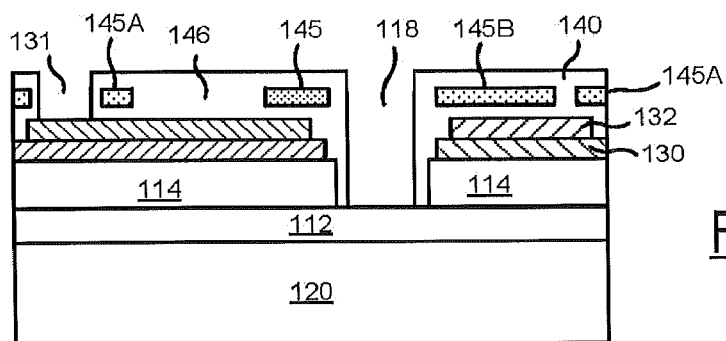


FIG. 60B

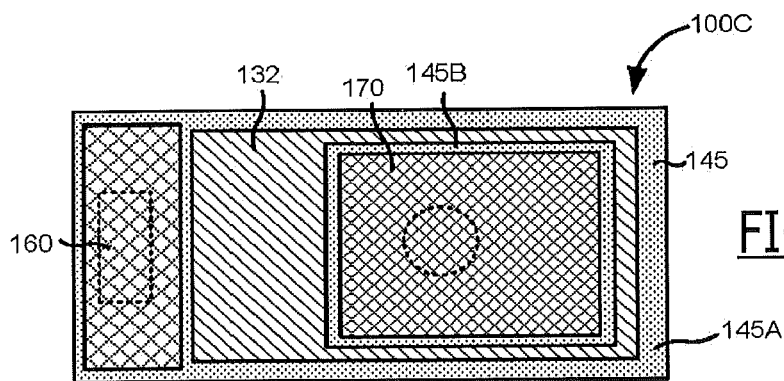


FIG. 61A

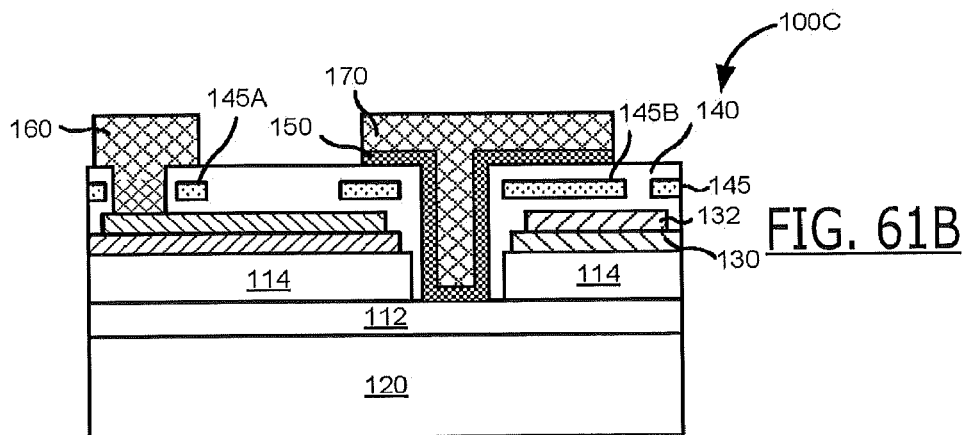
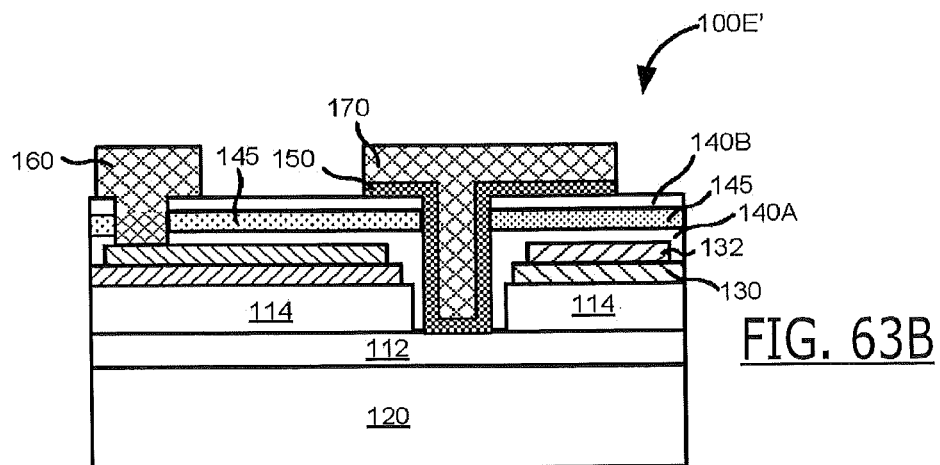
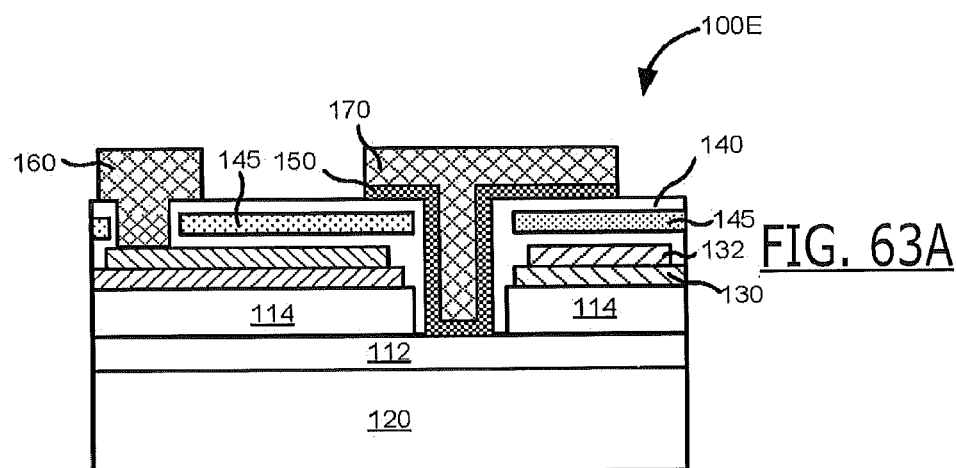
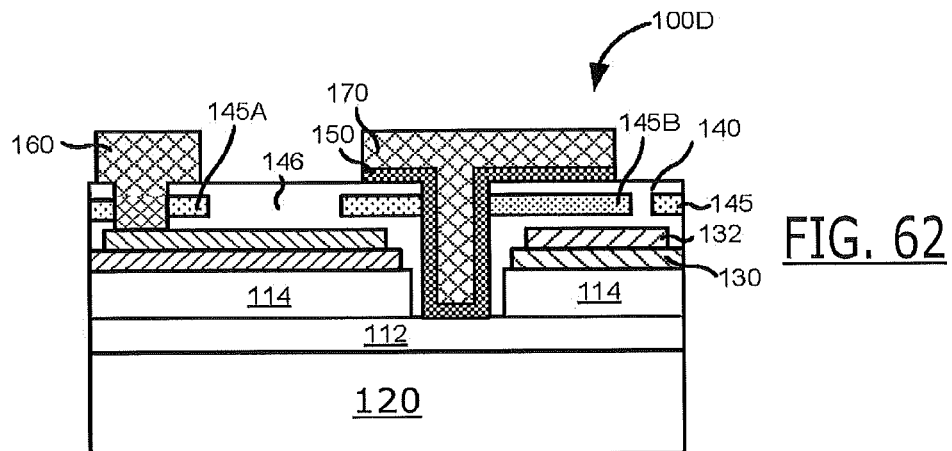


FIG. 61B



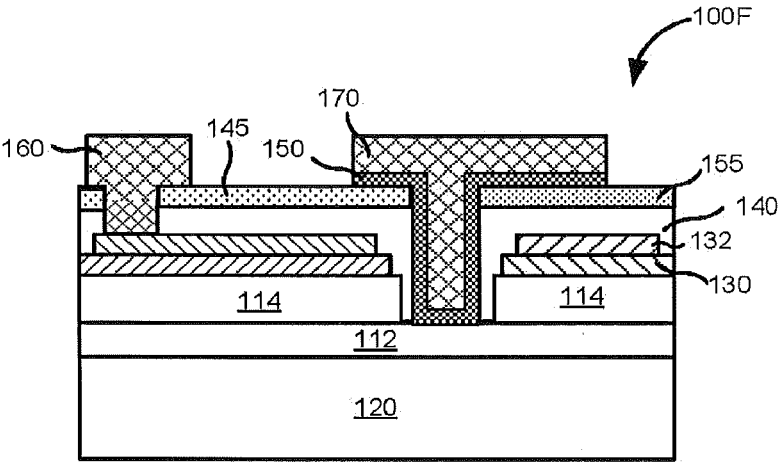


FIG. 64

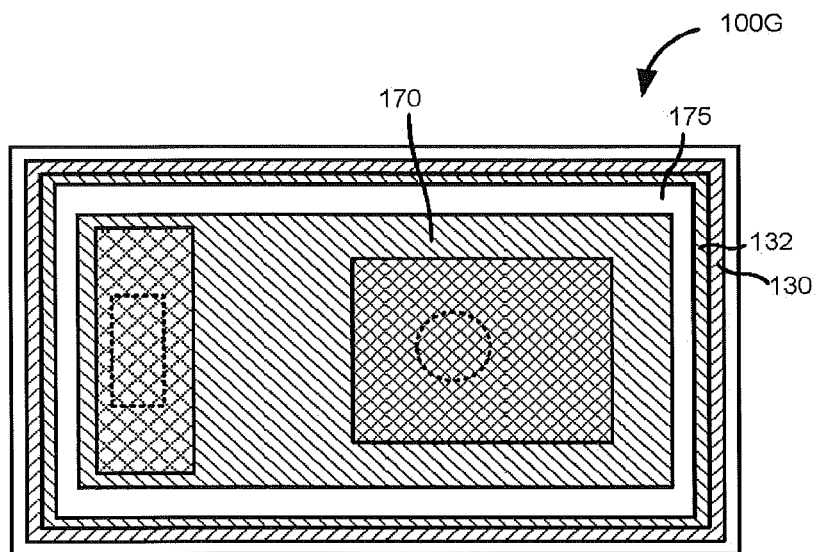


FIG. 65A

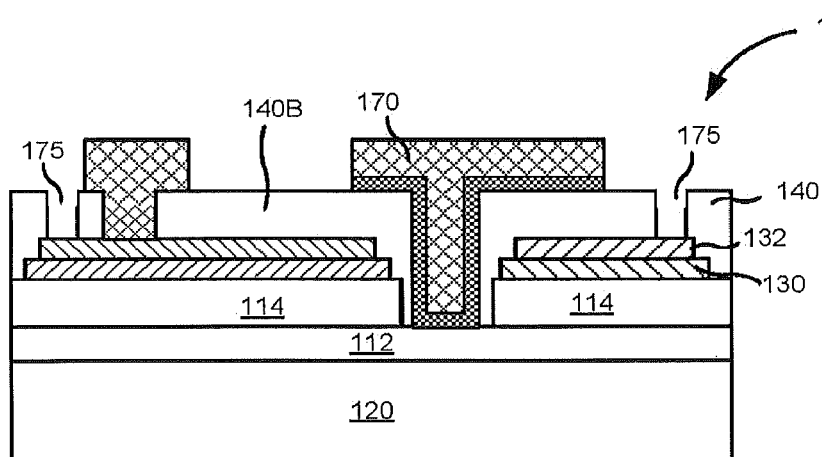


FIG. 65B

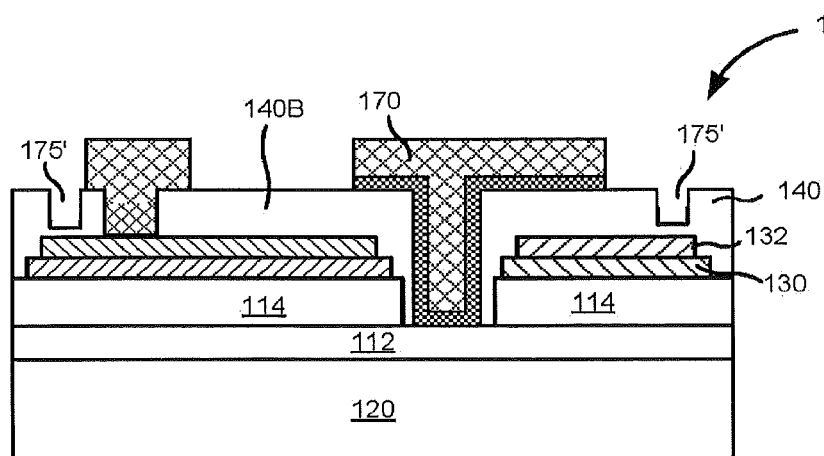


FIG. 65C

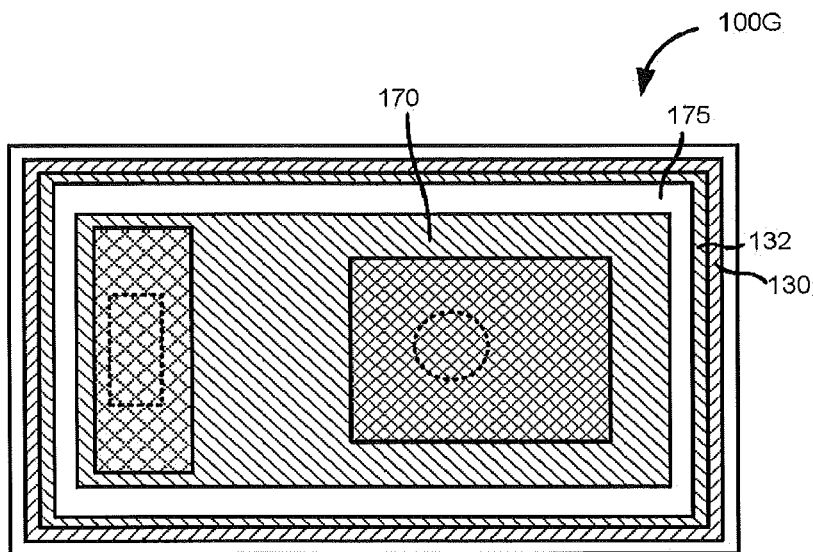


FIG. 66A

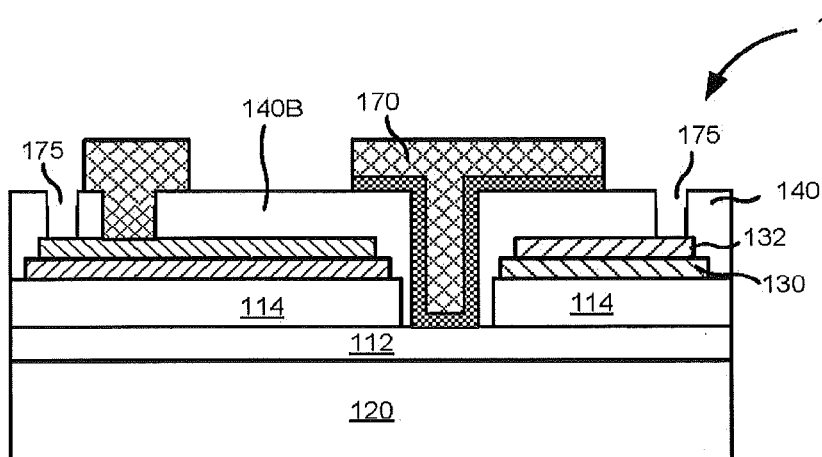


FIG. 66B

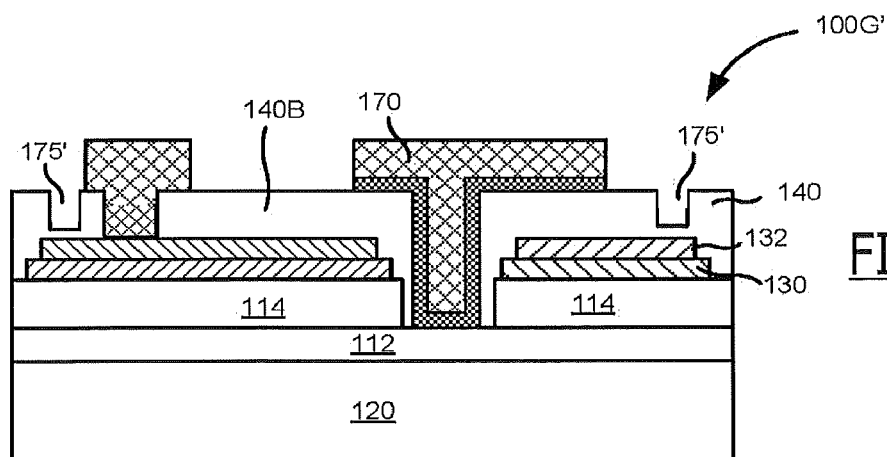


FIG. 66C

# WAFER LEVEL PACKAGING OF MULTIPLE LIGHT EMITTING DIODES (LEDs) ON A SINGLE CARRIER DIE

## CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] This application is a continuation of U.S. patent application Ser. No. 15/493,735 filed on Apr. 21, 2017, which is a continuation of U.S. patent application Ser. No. 13/801,743 filed on Mar. 13, 2013 and subsequently issued as U.S. Pat. No. 9,666,764 on May 30, 2017, which is continuation-in-part of U.S. patent application Ser. No. 13/608,397 filed on Sep. 10, 2012 and subsequently issued as U.S. Pat. No. 9,653,643 on May 16, 2017, which claims the benefit of U.S. Provisional Patent Application No. 61/621,746 filed on Apr. 9, 2012, wherein U.S. patent application Ser. No. 13/801,743 also claims the benefit of U.S. Provisional Patent Application No. 61/727,524 filed on Nov. 16, 2012, with the disclosures of all of the foregoing applications and patents hereby being incorporated by reference herein in their respective entireties.

## BACKGROUND

[0002] This invention relates to light emitting devices and assemblies and methods of manufacturing the same, and more particularly, to Light Emitting Diodes (LEDs) and assemblies thereof.

[0003] LEDs are widely known solid-state lighting elements that are capable of generating light upon application of voltage thereto. LEDs generally include a diode region having first and second opposing faces, and include therein an n-type layer, a p-type layer and a p-n junction. An anode contact ohmically contacts the p-type layer and a cathode contact ohmically contacts the n-type layer. The diode region may be epitaxially formed on a substrate, such as a sapphire, silicon, silicon carbide, gallium arsenide, gallium nitride, etc., growth substrate, but the completed device may not include a substrate. The diode region may be fabricated, for example, from silicon carbide, gallium nitride, gallium phosphide, aluminum nitride and/or gallium arsenide-based materials and/or from organic semiconductor-based materials. Finally, the light radiated by the LED may be in the visible or ultraviolet (UV) regions, and the LED may incorporate wavelength conversion material such as phosphor.

[0004] LEDs are increasingly being used in lighting/illumination applications, with a goal being to provide a replacement for the ubiquitous incandescent light bulb.

## SUMMARY

[0005] Various embodiments described herein provide methods of fabricating a plurality of Light Emitting Diodes (LEDs). An LED wafer is provided that includes a plurality of LED dies on an LED substrate, the plurality of LED dies including anode and cathode contacts on a face thereof that is remote from the LED substrate. A carrier wafer is also provided. The LED wafer and the carrier wafer are joined, so that the anode and cathode contacts are adjacent the carrier wafer and the LED substrate is remote from the carrier wafer. The LED wafer that is joined to the carrier wafer is shaped. Wavelength conversion material is applied to the LED wafer that is shaped. Finally, singulation is performed on the carrier wafer and the LED wafer, to

provide a plurality of LED dies, a respective one of which is joined to a respective carrier die, and having a length and width similar to the carrier die to which it is joined.

[0006] In some embodiments, the carrier wafer is scribed to define the plurality of carrier dies that are of similar length and width as the plurality of LED dies. The scribing may be performed before or after the joining. In other embodiments, the shaping comprises beveling the LED substrate. In still other embodiments, the shaping comprises texturing the LED substrate. In yet other embodiments, the shaping comprises thinning or removing the LED substrate, and the thinning or removing may be followed by texturing the LED dies. In yet other embodiments, the shaping comprises beveling the LED dies.

[0007] In some embodiments, singulating is followed by removing the respective carrier die. In other embodiments, singulating is followed by mounting at least one of the LED chips directly on a light fixture mounting board and mounting the light fixture mounting board including the at least one of the LED chips mounted directly thereon, in a light fixture housing to provide a light fixture. In still other embodiments, the mounting at least one of the LED dies directly on a light fixture mounting board and the mounting the light fixture mounting board in a light fixture housing are performed without providing a dome on the at least one of the LED dies.

[0008] In still other embodiments, the carrier wafer includes arrays of contacts on opposing faces thereof and an array of through-vias that electrically connect respective contacts on the opposing faces to one another. In other embodiments, the arrays of contacts on the opposing faces have different dimensions therebetween.

[0009] LEDs according to various other embodiments described herein may include a semiconductor LED die that includes an LED epi region and a carrier die that is electrically connected to the LED die, wherein the LED epi region and the carrier die have sides that are within 100  $\mu\text{m}$  of one another in length. In some embodiments, the LED epi region and the carrier die have same side lengths. In other embodiments, the LED produces at least 100, and in some embodiments at least 150, and in yet other embodiments at least about 200 lumens, of cool white light in some embodiments, per watt per square millimeter. In other embodiments, the LED produces at least 30 and in some embodiments at least 70, and in yet other embodiments at least about 140 lumens of warm white light per watt per square millimeter. In some embodiments, an anode and a cathode are both provided on the carrier die, remote from the LED die, and in other embodiments, the LED die further includes a substrate.

[0010] Light emitting diodes according to other embodiments can comprise a semiconductor LED die that includes an LED epi region and a carrier die that is electrically connected to the LED die, wherein the LED epi region and the carrier dies have sides that are within about 15% of one another in length. In other embodiments, the LED epi region and carrier die have areas that are within 70% of one another, within 85% of one another, or have same areas. In some embodiments, the LED epi region and the carrier die have the same side lengths. In still other embodiments, the LED may produce at least 45, and in some embodiments at least 100, and in other embodiments at least about 200 lumens, of cool white light in some embodiments, per watt per square millimeter. In still other embodiments, the LED may produce at least 30, and in some embodiments at least

70, and in other embodiments at least about 140 lumens of warm white light. In some embodiments, an anode and a cathode are both provided on the carrier die, remote from the LED die, and in other embodiments, the LED die further includes a substrate.

**[0011]** In still other embodiments, an LED comprises a semiconductor LED die and a carrier die that is electrically connected to the LED die, wherein the LED produces at least 45 lumens, of cool white light in some embodiments, per watt per square millimeter of area of the carrier die. In some embodiments, the LED produces at least 100 lumens, and in other embodiments at least about 200 lumens, of cool white light in some embodiments, per watt per square millimeter of the area of the carrier die. In still other embodiments, the LED produces at least 30 lumens, and in other embodiments at least 70 lumens, and in still other embodiments at least about 140 lumens of warm white light per square millimeter of area of the carrier die. In still other embodiments, the LED produces at least 45 lumens, and in some embodiments at least 100 lumens, and in other embodiments at least about 200 lumens, of cool white light in some embodiments, per watt per cubic millimeter of volume of the LED. In yet other embodiments, the LED produces at least 30 lumens, and in some embodiments at least 70 lumens, and in other embodiments at least about 140 lumens of warm white light per cubic millimeter of volume of the LED. In some embodiments, an anode and a cathode are both provided on the carrier die, remote from the LED die, and in other embodiments, the LED die further includes a substrate.

**[0012]** LEDs according to other embodiments include a semiconductor LED die and a carrier die that is electrically connected to the LED die, wherein the carrier die has an area of less than about 2 square millimeters, and in some embodiments less than about 1 square millimeter, and in other embodiments, an area of about 0.5 square millimeter or less. In any of these embodiments, the LED may have a height of about one millimeter. In still other embodiments, an LED comprises a semiconductor LED die and a carrier die that is electrically connected to the LED die, wherein the LED has a height of less than about 1.5 millimeters, and in some embodiments less than about 1 millimeter.

**[0013]** LEDs according to still other embodiments may include a semiconductor LED die that includes inner and outer faces and a plurality of sidewalls therebetween, and a carrier die that includes inner and outer faces and a plurality of sidewalls therebetween, wherein the inner face of the LED die is electrically connected to the inner face of the carrier die. A phosphor layer extends directly on the outer face of the LED die, directly on the plurality of sidewalls of the LED die and directly on the plurality of sidewalls of the carrier die. In some embodiments, the phosphor layer covers the outer face of the LED die and the plurality of sidewalls of the LED die and partially covers the plurality of sidewalls of the carrier die. In yet other embodiments, the phosphor layer protrudes beyond the carrier die in a direction along the faces of the carrier die.

**[0014]** Yet other embodiments may include a protective layer on the phosphor layer, remote from the LED die and the carrier die. In some embodiments, the phosphor layer comprises phosphor particles in a silicone binder, and the protective layer comprises a silicon layer that is free of the phosphor particles therein.

**[0015]** In still other embodiments, the outer face of the carrier die is configured for surface mounting of the LED. Moreover in some embodiments, the outer face of the carrier die includes a feature, such as a notch in a contact, configured to allow identification of an orientation of the LED.

**[0016]** LEDs according to still other embodiments may include a carrier, an LED epi region, a primary optic distinct from the LED epi region and a phosphor layer, wherein the carrier, LED epi region, primary optic and phosphor layer have outer edges that are within 100  $\mu\text{m}$  of one another, and in other embodiments have same size outer edges. As used herein, a "primary optic" means an optical element that causes the luminous flux from the LED to assume a specific illumination pattern. In some embodiments described herein, a substrate of the LED epi region may assume the role of a primary optic.

**[0017]** LEDs according to any of the embodiments described herein may be combined with a light fixture mounting board on which the carrier die is directly mounted and a light fixture housing in which the light fixture mounting board is mounted, to provide a light fixture. The light fixture is free of a dome between the carrier die and the light fixture housing.

**[0018]** An LED light fixture according to various embodiments described herein may include a light fixture mounting board, a plurality of LEDs directly mounted on the light fixture mounting board and a light fixture housing in which the light fixture mounting board including the plurality of LEDs thereon is mounted. The light fixture is free of a dome between a respective LED and the light fixture housing. The plurality of LEDs may comprise a plurality of semiconductor LED dies that are directly mounted on the light fixture mounting board without a carrier die therebetween.

**[0019]** Finally, methods of manufacturing LED light fixtures according to other embodiments described herein may include fabricating a plurality of LED wafers including wavelength converting material thereon at chip factory, dicing the LED wafers including the wavelength converting material thereon to produce a plurality of LED dies, and mounting the LED dies on a light fixture mounting board at a module factory or at a fixture factory and mounting the light fixture mounting board in a light fixture at a fixture factory. The fabricating, the dicing and the mounting bypass LED packaging factories. In these embodiments, the chip, module and fixture factories do not perform an operation of providing domes on the plurality of LED dies.

**[0020]** LED chips may be fabricated according to other embodiments described herein by providing an LED wafer that includes a plurality of LED dies, the plurality of LED dies including anode and cathode contacts on a face thereof, and providing a carrier wafer having first and second opposing faces, a plurality of internal contacts on the first face that are configured to electrically connect the anode and cathode contacts of at least two of the LED dies in series and/or in parallel when the carrier wafer is joined to the LED wafer, and a plurality of external anode contacts and a plurality of external cathode contacts. The LED wafer and the carrier wafer are joined so that the anode and cathode contacts of the LED dies are adjacent the first face of the carrier wafer and the plurality of internal contacts on the first face electrically connect the anode and cathode contacts of the at least two of the LED dies in series and/or in parallel. The LED wafer and the carrier wafer that have been joined are singulated to provide a plurality of LED chips, a respective



one of which includes a single carrier die, a respective single carrier die including a plurality of LED dies thereon that are electrically connected in series and/or in parallel, at least one of the plurality of the external anode contacts and at least one of the plurality of external cathode contacts.

**[0021]** In some embodiments, the LED wafer includes the plurality of LED dies on an LED substrate. Moreover, at least a portion of the LED substrate may be removed in some embodiments. In other embodiments, the LED wafer that is joined to the carrier wafer is shaped before the singulating. In still other embodiments, wavelength conversion material is applied to the LED wafer between the joining and the singulating. In yet other embodiments, the singulating is followed by mounting at least one of the LED chips directly on a light fixture mounting board, and mounting the light fixture mounting board including the at least one of the LED chips mounted directly thereon in a light fixture housing to provide a light fixture. The housing may be vehicle having headlight or taillight housing. Finally, in any of the above embodiments, the carrier wafer may further comprise at least one external thermal contact on the second face that is not electrically connected to the external anode contact or to the external cathode contact.

**[0022]** LED chips according to various embodiments, described herein may include a plurality of dies, a respective one of which includes an anode contact and a cathode contact on a face thereof. A carrier die is also provided having first and second opposing faces, a plurality of internal contacts on the first face that are configured to electrically connect the anode and cathode contacts of the plurality of LED dies in series and/or in parallel when the carrier die is electrically connected to the plurality of LED dies, and an external anode contact and an external cathode contact on the second face. The plurality of LED dies and the carrier die are joined to one another so that the anode and cathode contacts of the LED dies are adjacent the first face of the carrier die and the plurality of internal contacts on the first face electrically connect the anode and cathode contacts of the plurality of LED dies in series and/or in parallel.

**[0023]** In some embodiments, a respective LED die includes an LED epi region on an LED substrate. Moreover, a respective LED may include a sidewall, at least a portion of which is oblique to the face of the LED die. In other embodiments, a face of a respective LED die that is opposite the anode and cathode contacts includes a textured surface. In still other embodiments, a face of a respective LED die that is opposite the anode and cathode contacts includes a wavelength conversion material thereon. In yet other embodiments, a face of a respective LED die that is opposite the anode and cathode contacts includes a protective material thereon. Various combinations and subcombinations of texturing, wavelength conversion material and protective material may be provided. In still other embodiments, a mounting substrate is provided on the carrier die, remote from the plurality of LED dies. A dome is also provided that extends from a face of the mounting substrate, across the carrier die and the plurality of LED dies. Multiple domes also may be provided, a respective one of which is on a respective LED die, remote from the anode and cathode contacts thereof. Multiple lenses may also be provided on a respective die, remote from the anode and cathode contacts thereof. The LED chip may be combined with a light fixture

housing, as was described above. Finally, in any of the embodiments described herein, the carrier die may comprise silicon.

**[0024]** LED chips according to various other embodiments described herein can electrically connect a plurality of LED dies in series and/or in parallel using a patterned internal interconnection layer that is in the LED substrate. LED chips according to these embodiments may comprise an LED substrate including a plurality of LED dies, a respective LED die including an anode and a cathode. A patterned internal interconnection layer is provided in the plurality of LED dies that is configured to selectively electrically connect the anodes and cathodes of the plurality of LED dies in series and/or in parallel. An LED die anode contact is electrically connected to at least one of the anodes. An LED die cathode contact is electrically connected to at least one of the cathodes. In some embodiments, the patterned internal interconnection layer comprises a patterned internal metal layer that selectively extends between the plurality of LED dies to selectively electrically connect the anodes and cathodes of the plurality of LED dies in series and/or in parallel.

**[0025]** In some embodiments, the LED substrate includes beveled sidewalls between adjacent LED dies. Moreover, the LED substrate may include a beveled edge at a periphery thereof. A wavelength conversion material may be provided on the LED substrate remote from the carrier substrate, and extending onto the beveled sidewalls between adjacent LED dies. The wavelength conversion material layer may also extend onto the beveled edge at the periphery of the LED substrate. In other embodiments, the wavelength conversion material layer further extends onto a sidewall of the LED die at the periphery of the LED substrate.

**[0026]** LED chips according to any of the embodiments described above may also include a carrier die having first and second opposing faces, the carrier die having a first anode contact and a first cathode contact on the first face and a second anode contact and a second cathode contact on the second face. The carrier die is joined to the LED substrate so that the plurality of LED dies are adjacent the first face, the first anode contact is electrically connected to the LED die anode contact and the first cathode contact is electrically connected to the LED die cathode contact. A mounting substrate may also be provided on the second face of the carrier die and electrically connected to the second anode contact and the second cathode contact. The LED chip may also be combined with a light fixture housing in which the carrier die is mounted to provide a light fixture. The carrier die may also comprise at least one external thermal contact on the first and/or second face. The carrier die may comprise silicon in some embodiments and may also include a reflector in other embodiments.

**[0027]** A plurality of LED chips may be fabricated according to various embodiments described herein by providing an LED wafer that includes a plurality of LED dies, a respective LED die including an anode and a cathode. The LED wafer further includes a patterned internal interconnection layer in the plurality of LED dies that is configured to selectively electrically connect the respective anodes and cathodes of at least two of the LED dies in series and/or in parallel. The LED wafer further includes a plurality of LED die anode contacts and a plurality of LED die cathode contacts, a respective pair of which is electrically connected to a respective anode and cathode of a respective at least two

of the LED dies that are connected in series and/or in parallel. A carrier wafer is also provided, the carrier wafer having first and second opposing faces, a plurality of first contacts on the first face, a respective pair of which is configured to electrically connect to a respective pair of the LED die anode and cathode contacts of the respective at least two of the LED dies that are connected in series and/or in parallel when the carrier wafer is joined to the LED wafer, and a plurality of second contacts on the second face, a respective pair of which is electrically connected to a respective pair of the first contacts. The LED wafer and the carrier wafer are joined so that the LED die anode and cathode contacts are adjacent the first face of the carrier wafer and the respective pairs of the LED die anode and cathode contacts are electrically connected to a respective pair of the first contacts on the first face. The LED wafer and the carrier wafer that have been joined are then singulated to provide a plurality of LED chips, a respective one of which includes a single carrier die, a respective single carrier die including a plurality of LED dies thereon that are electrically connected in series and/or in parallel.

**[0028]** In some embodiments, the LED wafer includes a plurality of LED dies on a substrate, and the substrate is shaped between the joining and the singulating. In other embodiments, after the shaping, a wavelength conversion material is applied to the LED wafer that is joined to the carrier wafer, prior to singulating. In other embodiments, singulating may be followed by mounting at least one of the LED chips directly on a light fixture mounting board and mounting the light fixture mounting board including the at least one of the LED chips mounted directly thereon in a light fixture housing to provide a light fixture.

**[0029]** In some embodiments, the shaping of the substrate comprises beveling the substrate between adjacent ones of the LED dies. In some embodiments, the LED wafer includes a plurality of first trenches between adjacent LED dies that are connected in series and/or in parallel and a plurality of second trenches between groups of adjacent LEDs that are connected in series or in parallel, wherein the second trenches are deeper than the first trenches. In these embodiments, the beveling may expose the plurality of second trenches, but not expose the plurality of first trenches. Moreover, in these embodiments, the beveling may be followed by applying wavelength conversion material to the substrate that was beveled so that the wavelength conversion material extends on a face of the substrate that is remote from the carrier wafer, onto beveled surfaces of the substrate that were exposed by the beveling and onto the plurality of second trenches that were exposed. The wavelength conversion material may be applied by spraying in some embodiments.

**[0030]** The LED wafer itself may be fabricated by fabricating a plurality of the anodes and cathodes for the plurality of LED dies on the LED wafer, forming a first insulating layer on the plurality of anodes and cathodes, forming the patterned internal interconnection layer on the first insulating layer that is configured to selectively electrically connect the respective anodes and cathodes of at least two of the LED dies in series and/or in parallel, forming a second insulating layer on the patterned internal interconnection layer and forming the plurality of LED die anode contacts and LED die cathode contacts on the second insulating layer.

**[0031]** Moreover, prior to forming of the patterned internal interconnection layer, a plurality of first trenches may be

formed between adjacent LED dies that are connected in series and/or in parallel. In these embodiments, the patterned internal interconnection layer may be formed to extend across the first trenches between the anodes and the cathodes of the at least two of the LED dies that are selectively connected in series and/or in parallel. In other embodiments, a plurality of second trenches are also formed between groups of LED dies that are connected in series and/or in parallel. Moreover, in other embodiments, the plurality of second trenches between the groups of LED dies that are connected in series and/or in parallel are formed deeper than the plurality of first trenches between adjacent LED dies that are connected in series and/or in parallel.

**[0032]** In general, methods of fabricating LED chips according to various embodiments described herein can comprise providing an LED wafer that includes a plurality of LED dies, the plurality of LED dies including anode and cathode contacts on a face thereof; and providing a carrier wafer having first and second opposing faces, a plurality of internal contacts on the first face and at least one external anode contact and external cathode contact on the second face, wherein the LED wafer and/or the carrier wafer are configured to electrically connect the anode and cathode contacts of at least two of the LED dies in series and/or in parallel. The LED wafer and the carrier wafer are joined so that the anode and cathode contacts of the LED dies are adjacent the first face of the carrier wafer. The LED wafer and the carrier wafer that have been joined are then singulated to provide a plurality of LED chips, a respective one of which includes a single carrier die, a respective single carrier die including a plurality of LED dies thereon that are electrically connected in series and/or in parallel, an external anode contact and an external cathode contact. In some embodiments, the plurality of LED dies includes a patterned internal interconnection layer that is configured to selectively electrically connect the anode and cathode contacts of the at least two of the LED dies in series and/or in parallel. In other embodiments, the carrier wafer includes a plurality of contacts that are configured to selectively electrically connect the anode and cathode contacts of the at least two of the LED dies in series and/or in parallel.

**[0033]** Moreover, in general, LED chips according to various embodiments described herein include a plurality of LED dies in a common substrate, a respective one of which includes an anode contact and a cathode contact on a face thereof; and a carrier die having first and second opposing faces, a plurality of internal contacts on the first face and an external anode contact and an external cathode contact on the second face, wherein the plurality of LED dies in the common substrate and/or the carrier die is configured to electrically connect the anode and cathode contacts of the plurality of LED dies in series and/or in parallel. The plurality of LED dies and the carrier die are joined to one another so that the anode and cathode contacts of the LED dies are adjacent the first face of the carrier die and the anode and cathode contacts of the plurality of LED dies are connected in series and/or in parallel. In some embodiments, the plurality of LED dies includes a patterned internal interconnection layer that is configured to selectively electrically connect the anode and cathode contacts of the at least two of the LED dies in series and/or in parallel. In other embodiments, the carrier wafer includes a plurality of contacts that are configured to selectively electrically connect

the anode and cathode contacts of the at least two of the LED dies in series and/or in parallel.

#### BRIEF DESCRIPTION OF THE DRAWINGS

**[0034]** FIGS. 1A-1P and 1S-1U are cross-sections of one or more LEDs during intermediate and final wafer level packaging, according to various embodiments described herein.

**[0035]** FIGS. 1Q and 1R are bottom views of a carrier substrate of FIG. 1K.

**[0036]** FIG. 2 is a cross-section of an LED die in a light fixture according to various embodiments described herein.

**[0037]** FIG. 3 is a flowchart of LED fixture manufacturing according to various embodiments described herein.

**[0038]** FIG. 4 is a flowchart of conventional fixture manufacturing.

**[0039]** FIG. 5 is a more detailed flowchart of conventional fixture manufacturing.

**[0040]** FIG. 6 is a cross-section of LED dies in a light fixture housing according to various embodiments described herein.

**[0041]** FIGS. 7 and 8 are flowcharts of wafer level packaging of LEDs according to various other embodiments described herein.

**[0042]** FIG. 9A is a cross-section of a mounting board and a plurality of LED dies mounted thereon according to various embodiments described herein.

**[0043]** FIG. 9B is a plan view of FIG. 9A.

**[0044]** FIG. 10A is a cross-section of a conventional packing of LED dies on a carrier substrate.

**[0045]** FIG. 10B is a plan view of FIG. 10A.

**[0046]** FIG. 11 illustrates performance of wafer level packaged LEDs according to various embodiments described herein.

**[0047]** FIG. 12A is a photograph of a prototype LED according to various embodiments described herein, taken from the side.

**[0048]** FIG. 12B is a photograph of a prototype LED according to various embodiments described herein, taken from the bottom.

**[0049]** FIG. 12C is another photograph of a prototype LED according to various embodiments described herein, taken from the side.

**[0050]** FIG. 12D is a photograph of a prototype LED according to various embodiments described herein, taken from the top.

**[0051]** FIG. 12E is another photograph of a prototype LED according to various embodiments described herein, taken from the top.

**[0052]** FIG. 13A is a photograph of a prototype LED according to various embodiments described herein, taken from the bottom.

**[0053]** FIG. 13B is a photograph of a prototype LED according to various embodiments described herein, taken from the top.

**[0054]** FIG. 13C is a side view of a prototype LED according to various embodiments described herein.

**[0055]** FIG. 14 is a series of photographs of prototype LEDs according to various embodiments described herein, after wafer singulation and biasing of a backside contact.

**[0056]** FIG. 15 is a photograph illustrating relative sizes of a prototype LED according to various embodiments described herein (far right side) and other LEDs.

**[0057]** FIG. 16 is a series of photographs of prototype LEDs according to various embodiments described herein after singulation, mounted on a mounting board and mounted in an LED fixture.

**[0058]** FIGS. 17-27 are cross-sections of LED chips according to various embodiments described herein.

**[0059]** FIGS. 28A-28C are top views of LED dies on a carrier die according to various embodiments described herein.

**[0060]** FIGS. 29A-29C are top view, side view and bottom view, respectively, of an LED chip according to various embodiments described herein in an LED package.

**[0061]** FIGS. 30A-30C are cross-sections of an LED die according to various embodiments described herein.

**[0062]** FIG. 31 is a top view of lenses that can be placed on an LED die according to various embodiments described herein.

**[0063]** FIG. 32 is a cross-section of an LED die according to various embodiments described herein.

**[0064]** FIG. 33 includes photographs of a packaged LED component.

**[0065]** FIG. 34 is a bottom view of a carrier die according to various embodiments described herein.

**[0066]** FIG. 35 is a top view of an LED chip according to various embodiments described herein.

**[0067]** FIG. 36 is a flowchart of operations that may be performed to manufacture LED chips according to various embodiments described herein.

**[0068]** FIG. 37 is a cross-section of a light emitting diode according to various embodiments described herein.

**[0069]** FIGS. 38-49 are cross-sections of LED chips according to various embodiments described herein, during intermediate and final fabrication thereof.

**[0070]** FIGS. 50 and 52 are bottom views of LED chips according to various embodiments described herein.

**[0071]** FIGS. 53A and 53B are photographs of LED chips on mounting boards according to various embodiments described herein.

**[0072]** FIGS. 54 and 55 are cross-sectional view of light emitting diodes according to various embodiments described herein.

**[0073]** FIG. 56 is a detailed view of a portion of the LED structure shown in FIG. 55.

**[0074]** FIGS. 57A, 58A, 59A, 60A and 61A are plan views of intermediate LED device structures fabricated in accordance with some embodiments, and FIGS. 57B, 58B, 59B-59F, 60B and 61B are cross-sections of the intermediate LED device structures shown in FIGS. 57A, 58A, 59A, 60A, and 61A, respectively.

**[0075]** FIGS. 62, 63A, 63B and 64 are cross-sectional views of light emitting diodes according to various further embodiments described herein.

**[0076]** FIG. 65A is a plan view of an LED structure according to some further embodiments described herein.

**[0077]** FIGS. 65B and 65C are cross-sectional views of the LED structure of FIG. 65A according to various embodiments described herein.

**[0078]** FIG. 66A is a plan view of an LED structure according to some further embodiments described herein.

**[0079]** FIGS. 66B and 66C are cross-sectional views of the LED structure of FIG. 66A according to various embodiments described herein.

## DETAILED DESCRIPTION

**[0080]** The present invention now will be described more fully with reference to the accompanying drawings, in which various embodiments are shown. This invention may, however, be embodied in many different forms and should not be construed as limited to the embodiments set forth herein. Rather, these embodiments are provided so that this disclosure will be thorough and complete, and will fully convey the scope of the invention to those skilled in the art. In the drawings, the size and relative sizes of layers and regions may be exaggerated for clarity. Like numbers refer to like elements throughout.

**[0081]** It will be understood that when an element such as a layer, region or substrate is referred to as being “on” another element, it can be directly on the other element or intervening elements may also be present. Furthermore, relative terms such as “beneath” or “overlies” may be used herein to describe a relationship of one layer or region to another layer or region relative to a substrate or base layer as illustrated in the figures. It will be understood that these terms are intended to encompass different orientations of the device in addition to the orientation depicted in the figures. Finally, the term “directly” means that there are no intervening elements. As used herein, the term “and/or” includes any and all combinations of one or more of the associated listed items and may be abbreviated as “/”.

**[0082]** It will be understood that, although the terms first, second, etc. may be used herein to describe various elements, components, regions, layers and/or sections, these elements, components, regions, layers and/or sections should not be limited by these terms. These terms are only used to distinguish one element, component, region, layer or section from another region, layer or section. Thus, a first element, component, region, layer or section discussed below could be termed a second element, component, region, layer or section without departing from the teachings of the present invention.

**[0083]** Embodiments of the invention are described herein with reference to cross-sectional and/or other illustrations that are schematic illustrations of idealized embodiments of the invention. As such, variations from the shapes of the illustrations as a result, for example, of manufacturing techniques and/or tolerances, are to be expected. Thus, embodiments of the invention should not be construed as limited to the particular shapes of regions illustrated herein but are to include deviations in shapes that result, for example, from manufacturing. For example, a region illustrated or described as a rectangle will, typically, have rounded or curved features due to normal manufacturing tolerances. Thus, the regions illustrated in the figures are schematic in nature and their shapes are not intended to illustrate the precise shape of a region of a device and are not intended to limit the scope of the invention, unless otherwise defined herein.

**[0084]** Unless otherwise defined herein, all terms (including technical and scientific terms) used herein have the same meaning as commonly understood by one of ordinary skill in the art to which this invention belongs. It will be further understood that terms, such as those defined in commonly used dictionaries, should be interpreted as having a meaning that is consistent with their meaning in the context of the relevant art and this specification and will not be interpreted in an idealized or overly formal sense unless expressly so defined herein.

**[0085]** Some embodiments now will be described generally with reference to gallium nitride (GaN)-based light emitting diodes on silicon carbide (SiC)-based growth substrates for ease of understanding the description herein. However, it will be understood by those having skill in the art that other embodiments of the present invention may be based on a variety of different combinations of growth substrate and epitaxial layers. For example, combinations can include AlGaInP diodes on GaP growth substrates; InGaAs diodes on GaAs growth substrates; AlGaAs diodes on GaAs growth substrates; SiC diodes on SiC or sapphire ( $\text{Al}_2\text{O}_3$ ) growth substrates and/or a Group III-nitride-based diode on gallium nitride, silicon carbide, aluminum nitride, sapphire, zinc oxide and/or other growth substrates. Moreover, in other embodiments, a growth substrate may not be present in the finished product. For example, the growth substrate may be removed after forming the light emitting diode, and/or a bonded substrate may be provided on the light emitting diode after removing the growth substrate. In some embodiments, the light emitting diodes may be gallium nitride-based LED devices manufactured and sold by Cree, Inc. of Durham, N.C.

**[0086]** Various embodiments described herein can increase the lumen/dollar performance of LEDs by performing packaging-like process steps at the wafer level, to allow reduction of handling and assembling of discrete level LED dies or chips into a package. Thus, various embodiments described herein can merge chip or die fabrication and packaging into fewer steps, to thereby allow leveraging of the parallel process cost reduction available by performing wafer level processing of the die rather than component level processing. Various embodiments described herein can move die and component singulation to the end of the LED lamp manufacturing line. Moreover, various embodiments described herein can also reduce redundant characterization steps between the LED die and LED package testing, which can allow further reduction in manufacturing costs, such as labor, work-in-process time and capital expense. Finally, various embodiments described herein can tightly pack LED dies on a mounting board to allow increased luminous efficiency.

**[0087]** Various embodiments described herein may arise from recognition that, conventionally, LED dies are singulated and sorted, and placed upon die sheets, which are shipped to a components factory, only to have the dies removed from the die sheets and repopulated onto panels. Accordingly, conventional LED manufacturing begins with a wafer, singulates the wafer and then basically reassembles the wafer, only to repeat the process of singulation followed by testing and measurements again. Various embodiments described herein can provide methods of fabricating LEDs and methods of manufacturing LED light fixtures that can at least partially reduce or eliminate these redundancies. Moreover, various embodiments described herein can provide LEDs and LED light fixtures so manufactured.

**[0088]** FIG. 1A is a cross-sectional view of an LED wafer including a plurality of LED dies. Referring to FIG. 1A, the LED wafer 100 includes diode regions 110 having first and second opposing faces 110a, 110b, respectively, and including therein an n-type layer 112 and a p-type layer 114. Other layers or regions may be provided, which may include quantum wells, buffer layers, etc., that need not be described herein. Moreover, the n-type layer 112 and the p-type layer 114 may be adjacent one another to form a p-n junction or

may be spaced apart from one another. Either or both layers may be at a surface of the diode region **110** or may be buried within the diode region. Anode contacts **160** ohmically contact the p-type layer **114** and extends on the first face **110a**. The anode contacts **160** may directly ohmically contact the p-type layer **114**, or may ohmically contact the p-type layer **114** by way of one or more conductive vias **162** and/or other intermediate layers. Cathode contacts **170** ohmically contact the n-type layer **112** and also extend on the first face **110a**. The cathode contacts may directly ohmically contact the n-type layer **112**, or may ohmically contact the n-type layer **112** by way of one or more conductive vias **172** and/or other intermediate layers. As illustrated in FIG. 1A, the anode contacts **160** and the cathode contacts **170** that both extend on the first face **110a** are coplanar.

[0089] The diode region **110** also may be referred to herein as an “LED epi region” or simply as an “LED epi”, because it is typically formed epitaxially on a substrate **120**. For example, a Group III-nitride based LED epi **110** may be formed on a silicon carbide growth substrate. In some embodiments, the growth substrate may be present in the finished product. In other embodiments, the growth substrate may be thinned or removed. In still other embodiments, another substrate may be provided that is different from the growth substrate, and the other substrate may be bonded to the LED after removing the growth substrate. The LED epi **110** defines a plurality of LED dies **110'**.

[0090] As also shown in FIG. 1A, a substrate **120**, such as a transparent silicon carbide growth substrate or a transparent sapphire growth substrate, is included on the second face **110b** of the diode region **110**. The substrate **120** includes an inner face **120c** adjacent the second face **110b** of the diode region **110** and an outer face **120b**, remote from the inner face **120c**.

[0091] FIG. 1B illustrates a carrier wafer **180** that includes a body **182** that may comprise aluminum nitride (AlN), silicon and/or aluminum oxide. In other embodiments, metal core substrates, printed circuit boards and/or other carrier wafers may be used. The carrier wafer **180** includes a carrier wafer face **182a**, and an anode pad **184** and a cathode pad **186** thereon. The anode and cathode pads may comprise silver-plated copper and/or other conductive materials. A packaged device anode **192** and a packaged device cathode **194** may be provided on a second face **182b** of the body **182**, and may be connected to the anode pad **184** and cathode pad **186**, respectively, using internal vias and/or conductive layers **196** that extend in and/or around the body **182**. The carrier wafer **180** may also include electrostatic discharge protection devices therein. In some embodiments, the body **182** comprises silicon and the vias **196** may be fabricated using conventional Through Silicon Via (TSV) technology. In some embodiments, the carrier wafer **180** is about 100  $\mu\text{m}$  thick, and in other embodiments, the carrier wafer may be between about 30  $\mu\text{m}$  and about 500  $\mu\text{m}$  thick. The anode and cathode pads and the packaged device anode and cathode may be less than about 10  $\mu\text{m}$  thick, in some embodiments.

[0092] In FIG. 1B, the anode pad **184** and the packaged device anodes **192** are of approximately the same size and shape. Moreover, the cathode pads **186** and the packaged device cathodes **194** are also of approximately the same size and shape. However, this need not be the case. For example, as shown in FIG. 1K, the packaged device anodes **192** and/or

the packaged device cathodes **194** may be smaller than the corresponding anode pads **184** and cathode pads **186**. Thus, more separation may be provided between the packaged device anodes **192** and cathodes **194** to provide a more package-friendly environment, since the placement ability at the packaging manufacturing level may be lower. As illustrated in FIG. 1K, a wider gap between the packaged device anode **192** and the packaged device cathode **194** may be provided. Thus, the packaged device anodes **192** and/or the packaged device cathodes **194** may be configured for surface mounting. Accordingly, FIGS. 1B and 1K illustrate a carrier wafer that includes arrays of contacts on opposing faces thereof, and an array of through vias that electrically connect a respective contact on the opposing faces to one another. Moreover, FIG. 1K illustrates embodiments wherein the corresponding contacts in the arrays of contacts on the opposing faces have different dimensions therebetween.

[0093] More specifically, FIGS. 1Q and 1R illustrate configurations of anode pads **184**, packaged device anodes **192**, cathode pads **186** and packaged device cathodes **194** on a carrier wafer **180**, according to various embodiments described herein. As shown in FIG. 1Q, the packaged device anode **192** may be larger than the anode pad **184**, and the packaged device cathode **194** may be smaller than the cathode pad **186**, to facilitate surface mounting of the LED. In other embodiments, as shown in FIG. 1R, there may be more spacing between the packaged device anode **192** and the packaged device cathode **194**, than between the anode pad **184** and the cathode pad **186**, to facilitate surface mounting of the LED. Moreover, a feature, such as a notch **193** in the packaged device cathode **194** may be provided to allow identification of an orientation of the LED. Other types of orientation identification features may also be provided according to various other embodiments, and the orientation identification features may be provided in the packaged device anode **192**, in the packaged device cathode **194** and/or on the body **180** of the carrier die. Accordingly, the carrier die may be configured for surface mounting of the LED and/or to allow identification of an orientation of the LED. In some embodiments, when the carrier has dimensions of about 0.7 mm $\times$ 0.7 mm, the packaged device cathode **194** may have dimensions of about 0.65 mm $\times$ about 0.25 mm, the packaged device anode **192** may have dimensions of 0.65 mm $\times$ 0.25 mm, and the spacing between the packaged device anode **192** and the packaged device cathode **194** may be about 0.15 mm.

[0094] FIG. 1A illustrates LED wafers that are configured for flip-chip mounting on a carrier wafer such as the carrier wafer **180** of FIG. 1B. Various configurations of flip-chip mounted light emitting diode dies may be used in the LED wafers in various embodiments described herein. Other light emitting devices according to various embodiments described herein may be configured for non-flip-chip mounting on a mounting substrate, as described and illustrated, for example, in U.S. Patent Application Publication 2011/0031502 to Bergmann et al. entitled “Light Emitting Diodes Including Integrated Backside Reflector and Die Attach”, filed Aug. 10, 2009, assigned to the assignee of the present application, the disclosure of which is hereby incorporated herein by reference in its entirety as if set forth fully herein. Moreover, other light emitting devices according to various embodiments described herein may be configured as vertical light emitting devices, as described and illustrated, for example, in U.S. Pat. No. 6,791,119 to Slater, Jr et al.,

entitled “Light Emitting Diodes Including Modifications for Light Extraction”, filed Jan. 25, 2002, assigned to the assignee of the present application, the disclosure of which is hereby incorporated herein by reference in its entirety as if set forth fully herein.

**[0095]** FIG. 1B also illustrates a plurality of scribe lines **190** in the second face **182b** of the carrier wafer **180**, that define a plurality of carrier dies that are of similar length and width as the plurality of LED dies **110'** on the LED wafer **100**. Scribing may take place using a diamond tool, a laser and/or other conventional scribing techniques. Moreover, scribing may not need to be performed in FIG. 1B, but may be performed after attaching the LED wafer **100** to the carrier wafer **180**, as will be described below.

**[0096]** Accordingly, FIG. 1A illustrates providing an LED wafer **100** that includes a plurality of LED dies **110'** on an LED substrate **120**, the plurality of LED dies **110'** including anode and cathode contacts **160**, **170**, on a face **110a** thereof that is remote from the LED substrate **120**. FIG. 1B illustrates providing a carrier wafer **180** and also illustrates an optional scribing **190** of the carrier wafer, to define a plurality of carrier dies **180'** that are of similar length and width as the plurality of LED dies **110'**.

**[0097]** Referring now to FIG. 1C, the LED wafer **100** and the carrier wafer **180** are joined, so that the anode and cathode contacts **160**, **170** are adjacent the carrier wafer **180**, and the LED substrate **120** is remote from the carrier wafer **180**. More specifically, as illustrated in FIG. 1C, the LED wafer **100** is mounted on the carrier wafer **180**, such that the first face **110a** is adjacent the first carrier wafer face **182a**, the second face **110b** is remote from the carrier wafer **180**, the anode pads **184** are adjacent the anode contacts **160**, and the cathode pads **186** are adjacent the cathode contacts **170**. In some embodiments, a bonding layer, such as a eutectic gold/tin solder layer **188**, is used to electrically, thermally and/or mechanically connect the anode contacts **160** to the anode pads **184**, and the cathode contacts **170** to the cathode pads **186**. In other embodiments, direct attachment of the anode contacts **160** to the anode pads **184**, and direct attachment of the cathode contacts **170** to the cathode pads **186** may be provided, for example using thermocompression bonding and/or other techniques.

**[0098]** Referring now to FIG. 1D, the LED substrate **120** that is joined to the carrier wafer **180** is shaped. In FIG. 1D, shaping takes place by forming bevels **210** in the second face **120b** of the substrate **120**, for example using a saw blade, laser, wet and/or dry etching, and/or other conventional beveling techniques. Various shapes of beveling and/or faceting may be provided. For example, an “X”-shaped cut may be performed on the outer face, and sidewall beveling **210** may also be performed. Prior to or after beveling, the substrate **120** may be thinned. In other embodiments, the entire LED substrate **120** may be removed. Moreover, in some embodiments, if scribing of the carrier wafer **180** did not take place prior to attachment in FIG. 1C, scribing may take place after attachment in FIG. 1D.

**[0099]** In FIG. 1D, the bevels **210** extend into the second face **120b** of the substrate **120**. However, deeper beveling may also be provided that extends through the substrate **120**. In other embodiments, the bevels may extend into, and in some embodiments through, the diode regions **110**. In yet other embodiments, the bevels may extend into the body **182** of the carrier wafer **180**. Thus, for example, as illustrated in FIG. 1L, the bevels **210'** extend through the substrate **120**,

through the diode region **110** and into the body **182** of the carrier wafer **180**. By providing deeper bevels, a subsequent coating of phosphor (described below) can extend along the edges or sidewalls of the diode region **110**, and can reduce or prevent production of undesired edge emission from the LED. For example, undesired blue edge emission may be reduced or prevented when a blue LED is used with yellow phosphor that extends along the edge or sidewalls of the diode region.

**[0100]** As was also noted above, in some embodiments, the entire LED substrate **120** may be removed. Thus, as illustrated in FIG. 1M, the substrate **120** is entirely removed. Substrate removal may take place prior to or after beveling. In other embodiments, the substrate may be thinned prior to beveling, and the remaining substrate may be removed after beveling.

**[0101]** Referring now to FIG. 1E, a wavelength conversion material **220** is applied to the LED substrate **120** that has been shaped. The wavelength conversion material **220**, also generally referred to herein as “phosphor”, may be provided according to various configurations. In some embodiments, the diode regions **110** are configured to emit blue light, for example light having a dominant wavelength of about 450-460 nm, and the wavelength conversion layer **220** comprises yellow phosphor, such as YAG:Ce phosphor, having a peak wavelength of about 550 nm. In other embodiments, the diode region **110** is configured to emit blue light upon energization thereof, and the wavelength conversion material **220** may comprise a mixture of yellow phosphor and red phosphor, such as CASN-based phosphor. In still other embodiments, the diode region is configured to emit blue light upon energization thereof, and the wavelength conversion material **220** may comprise a mixture of yellow phosphor, red phosphor and green phosphor, such as LuAG:Ce phosphor particles. Moreover, various combinations and subcombinations of these and/or other colors and/or types of phosphors may be used in mixtures and/or in separate layers. Various techniques may be used to apply the phosphor, including spraying, coating and/or other techniques. Phosphor preforms also may be applied.

**[0102]** Similarly, for deep beveling embodiments that were illustrated in FIG. 1M, a wavelength conversion material **220** may be applied according to any of the embodiments described above, as illustrated, for example, in FIG. 1N. As was already noted, by coating the diode region **110** with phosphor, undesired emission of, for example, excess blue light from the sidewalls or edge of the diode region may be reduced or prevented.

**[0103]** Referring now to FIG. 1F, singulation **230** is then performed on the carrier wafer **180** that has been scribed, and on the LED wafer **100** that has been joined to the carrier wafer **180** and that has been shaped **210** and that has wavelength conversion material **220** applied thereto. Singulation may take place along singulation lines **230**, that correspond to the scribe lines **190**, using conventional singulation techniques. As shown in FIG. 1G, the singulation provides a plurality of LED dies **110'**, a respective one of which is joined to a respective carrier die **180'**. An anode **192** and a cathode **194** are provided on the carrier die **182**, remote from the LED die **110**. Moreover, a substrate **120** may also be provided. Note that only one of these LED dies/carrier dies is shown in FIG. 1G. FIG. 1O illustrates a singulated LED device of FIG. 1N, wherein the substrate

**120** is not included, and the phosphor coating **220** extends along the sidewalls of the LED dies **110'**.

**[0104]** Referring back to FIG. 1D, substrate shaping by beveling was illustrated. However, other techniques of substrate shaping may be provided, as will now be described in connection with FIGS. 1H-1J. Specifically, FIG. 1H illustrates providing texturing **212** on the outer substrate face, followed by application of wavelength conversion material **220**. Texturing may take place using etching and/or other techniques. Substrate thinning may also take place. In other embodiments, the entire LED substrate **120** may be removed, and texturing of the second face of the diode regions **110** may take place.

**[0105]** FIG. 1I illustrates singulation of the textured devices, as was also illustrated in FIG. 1F. FIG. 1J illustrates a resulting LED die **110''** having a textured substrate. It will also be understood that, in other embodiments, beveling and texturing may be combined, for example by using a saw blade to provide the bevels of FIG. 1D and then texturing on the exposed surface as illustrated in FIG. 1H. In yet other embodiments, the substrate **120** may be removed, and texturing of the second (outer) face **110b** of the LED **110'** may be provided. FIG. 1P illustrates the singulation of the textured devices, which were subject to deep beveling, as was illustrated in FIG. 1N. The texturing may extend on the second (outer) face **110b** of the LED die **110''** and/or may extend along the sidewalls thereof. In addition, an X-cut may also be provided on the second face **110b** of the LED die **110''**.

**[0106]** FIGS. 1S-1U also illustrate singulation of the devices according to various other embodiments described herein. Specifically, in FIG. 15, the deep beveled wafers of FIG. 1L that include a shaped substrate **120** are singulated after a phosphor layer is applied thereto. Thus, as shown in FIG. 15, the semiconductor LED die **110'** includes an outer face **120b**, an inner face **110a**, and a plurality of sidewalls **110c** therebetween. The carrier die **180'** includes an outer face **182a**, an inner face **182b**, and a plurality of sidewalls **182c** therebetween. The inner face **110a** of the LED die **110'** is electrically connected to the inner face **182b** of the carrier die **182**. A phosphor layer **220** extends directly on the outer face **120b** of the LED die **110'**, directly on the plurality of sidewalls **110c** of the LED die **110'** and directly on the plurality of sidewalls **182c** of the carrier die. In some embodiments, the phosphor layer covers the outer face **120b** of the LED die **110'** and the plurality of sidewalls **110c** of the LED die **110'**, and partially covers the plurality of sidewalls **182c** of the carrier die **180'**. As also shown in FIG. 1S, the phosphor layer **220** may protrude beyond the carrier die **182** in a direction along the inner face **182b** and outer face **182a** of the carrier die **180'**. Thus, in FIG. 1S, the phosphor layer may protrude in the horizontal direction beyond the sidewalls **182c** of the carrier die body **182**. The extent of protrusion of the phosphor layer **220** may be controlled, for example, by the depth and/or profile of the shaping that takes place, by the thickness of the phosphor layer that is provided and/or by other techniques.

**[0107]** FIG. 1T illustrates other embodiments wherein texturing **212** of the outer face **120b** of the semiconductor LED die **120** is provided, as was also illustrated, for example, in FIG. 1J.

**[0108]** FIG. 1U illustrates the addition of a protective layer **222** on the phosphor layer **220**. In some embodiments, the phosphor layer **220** may comprise phosphor particles in

a binder, such as a silicone binder, and the protective layer **222** may comprise a layer, such as a silicone layer, comprising for example the same silicone as the silicone binder, that is free of the phosphor particles therein. The protective layer **220** may be added prior to and/or after singulation.

**[0109]** FIGS. 1G, 1J, 1O, 1P, 1S, 1T and 1U also illustrate LEDs according to other embodiments that comprise a carrier **180'**, an LED epi region **110**, a primary optic, such as substrate **120**, that is distinct from the LED epi region **110**, and a phosphor layer **220**. The carrier **180'**, the LED epi region **110**, the primary optic **120** and the phosphor layer **220** have outer edges that are within 100  $\mu\text{m}$  of one another in some embodiments, and in other embodiments, have same size outer edges. In some embodiments, the primary optic can be other suitable materials and/or constructions, such as a molded silicone lens, for example when the substrate is removed.

**[0110]** FIG. 2 illustrates the packaging of an LED die, for example an LED die of FIGS. 1G, 1J, 1O, 1P and/or 1S-1U, into an LED fixture. Specifically, as shown in FIG. 2, at least one of the LED dies **320**, which may correspond to the product of FIGS. 1G, 1J, 1O, 1P and/or 1S-1U is directly mounted on a light fixture mounting board **310**. The light fixture mounting board **310** is then mounted in a light fixture housing **330** to provide a light fixture **340**. As illustrated in FIG. 2, the light fixture is free of a dome between the LED die **320** and the light fixture housing **330**. It will be understood that, as used herein, a "dome" may include a smooth or faceted structure. It will be understood that light fixture **340** is illustrated in FIG. 2 in a greatly simplified form, and does not include driver circuitry, power supplies, heat sinking and/or other conventional elements. Moreover, the housing **330** may include opaque/reflective portions **330a** and transparent portions **330b**, to allow light to emerge from the housing.

**[0111]** FIG. 3 is a flowchart of LED fixture manufacturing according to various embodiments described herein. Referring to FIG. 3, an LED wafer is fabricated at Block **410**, for example as was illustrated in FIG. 1A. At Block **420**, a carrier wafer is fabricated, as was illustrated, for example, in FIG. 1B or 1K, and is optionally scribed. At Block **430**, the LED wafer and the carrier wafer are joined, as was illustrated, for example, in FIG. 1C. Scribing also may optionally take place. The substrate is then shaped at Block **440**, as was illustrated, for example, in FIGS. 1D, 1H, 1L and/or 1M. At Block **450**, phosphor is applied, as was illustrated, for example, in FIGS. 1E, 1H and/or 1N.

**[0112]** As also illustrated in FIG. 3, all of the operations of Blocks **410-450** may take place at a "chip factory". Thus, substrate carrier joining (Block **430**), substrate shaping (Block **440**) and phosphor application (Block **450**) may be performed at a wafer level at a chip factory rather than being applied at a die level at a package factory.

**[0113]** Continuing with the description of FIG. 3, testing of the wafers that are provided by the chip factory at Block **450** may then be performed at Block **460** and singulation may also be performed at Block **460**, as was illustrated, for example, in FIG. 1F and/or 1I. Testing may be performed prior to and/or after singulation at Block **460**. Testing and singulation may take place at a separate "module factory", or may take place at the chip factory or at a "fixture factory". Accordingly, in some embodiments, the completed wafers from Block **450** may be shipped to a fixture factory, which is then responsible for testing, singulation and integration

into a fixture. Optionally, the entire carrier die **180'** of FIG. **1G** or **1J** may be removed at any desired point in the fixture manufacturing process, if desired. Then, at Block **480**, the LED, for example the LED of FIGS. **1G**, **1J**, **1O**, **1P** and/or **1S-1U**, is mounted on a fixture board, as was illustrated, for example, in FIG. **2**, and at Block **490**, the fixture board is mounted on the fixture housing, as also was illustrated in FIG. **2**.

**[0114]** Various embodiments described herein, as illustrated, for example, in FIG. **3**, may eliminate the need for a package factory and may also eliminate the need for a module factory. The chip maker may ship completed wafers from the chip factory to a fixture factory or a module factory.

**[0115]** In sharp contrast, FIG. **4** provides an overview of conventional fixture manufacturing. An LED wafer is fabricated and singulated at chip factory, as illustrated in Block **510**. The singulated LED chips are then placed on die sheets and sent to a package factory, where the dies are packaged at Block **520**. For example, the dies are mounted on a submount or other substrate, encapsulated, and a dome is placed on the encapsulated package. The packaged LEDs are then shipped to a module factory or a fixture factory, where they are mounted on a fixture board, as shown at Block **530**. At the fixture factory, the packaged LEDs are mounted in a fixture housing, as shown at Block **540**.

**[0116]** FIG. **5** illustrates a more detailed flowchart of conventional fixture manufacturing. As illustrated at Block **610**, the LED wafer is fabricated. Then, at Block **620**, wafer level operations are performed (e.g., die contact formation and electrical testing). At Block **630**, the LED dies are singulated, tested and sorted. At Block **640**, the sorted LED dies are assembled onto sorted die sheets. The sorted die sheets are then shipped to a package factory, where at Block **660**, a panel is populated and phosphor is applied, and the panel is tested, singulated, packaged and sorted again. Finally, operations of Block **530** and **540** are performed.

**[0117]** As was described above, various embodiments described herein can provide improved efficiency in the fabrication process for LEDs by eliminating/reducing fabrication steps and even eliminating the need for one or two separate factories (a packaging factory and/or a module factory). Moreover, improved luminous efficiency also may be provided according to various embodiments described herein. For example, FIG. **6** illustrates an LED light fixture **340** that includes a light fixture mounting board **310** and a plurality of LED dies **110'/110"**, such as the LED dies of FIGS. **1G**, **1J**, **1O**, **1P** and/or **1S-1U** directly mounted thereon. LED dies according to any of the embodiments described herein may be used. A light fixture housing **330** is provided, wherein the light fixture mounting board **310** including the plurality of LED dies **110'/110"** mounted thereon, is mounted in the housing **330**. As shown in FIG. **6**, the LED dies may be mounted in the housing without the need for encapsulation and a dome. Thus, the light fixture **340** is free of a dome between a respective LED die **110'/110"** and the light fixture housing **330**. Because a dome is not needed, the LEDs may be packed much more tightly than is conventionally the case. Higher light output per unit area may thereby be provided. Moreover, although embodiments of FIG. **1G** are illustrated in FIG. **6**, the carrier dies **180'** may optionally also be removed from the LED dies **110'** prior to mounting on the LED mounting board **310**, so that

the plurality of LED dies **110'** may be directly mounted on the light fixture mounting board without a carrier die therebetween.

**[0118]** FIG. **7** is a flowchart of LED wafer/carrier wafer fabrication according to various other embodiments. As illustrated in FIG. **7**, an LED wafer **100** is manufactured at Block **702**, as was illustrated, for example, in FIG. **1A**, and wafer processing is performed at Block **704** in order to provide standard wafer fabrication operations including metallization. At Block **706**, substrate shaping, such as substrate thinning including substrate removal and/or texturing may optionally take place, to provide a final LED wafer thickness of, for example, between about 330  $\mu\text{m}$  and about 390  $\mu\text{m}$ , as was illustrated, for example, in FIG. **1M**. At Block **712**, a carrier, such as a silicon wafer, is fabricated, through vias are formed at Block **714** and both faces of the carrier wafer are patterned at Block **716** to provide contacts, as was illustrated, for example, in FIGS. **1B** and **1K**. At Block **722**, the wafer and carrier are aligned and then bonded at Block **724**, for example using eutectic bonding, as was illustrated, for example, in FIG. **1C**. The bonded devices then proceed to backend processing operations at Block **726**, as will be described in FIG. **8**. It will be understood by those having skill in the art that all of the operations of FIG. **7** may be performed at a chip factory, also commonly referred to as a "Fab".

**[0119]** FIG. **8** illustrates the backend processing flow that may also take place at a chip factory or at a module/fixture factory. Referring to FIG. **8**, at Block **732**, the LED wafer and carrier that are bonded together is mounted on a tape. At Block **734**, wafer shaping may take place if applicable. The shaping may include forming an "X"-cut or other top cut along with other operations to texture the LED substrate or the LED die, as was illustrated, for example, in FIG. **1H**. A bevel cut may also be performed at Block **734**, as was illustrated, for example, in FIGS. **1D**, **1L** and/or **1M**. Scribing of the carrier may also take place at Block **736** using, for example, a straight cut, as was illustrated, for example, at FIG. **1C**. A post-saw cleanup using, for example, Reactive Ion Etching (RIE) can then be performed. Phosphor and an optional protective layer are then deposited, for example by spraying or other coating techniques at Block **738**, as was illustrated, for example, in FIGS. **1E**, **1H** and **1N**. An initial probe, such as a color target probe, may be performed. Singulation then takes place at Block **742**, for example by taking apart the dies using a slotted anvil, as was illustrated, for example, in FIGS. **1F** and **1I**. The tape may then be stretched to further separate the singulated devices and a post-stretch cure of the tape may then be performed if desired. Electrical and optical testing may then take place at Block **744** and an optical inspection, such as a visual inspection, may take place at Block **746**. The LEDs are then binned and sorted at Block **748**. It will be understood that operations **732-748** of FIG. **8** may all take place at the chip factory.

**[0120]** FIGS. **9A**, **9B**, **10A** and **10B** illustrate an increased packing density or light output per unit area/volume/height that may be provided according to various embodiments described herein. FIG. **9A** is a cross-section and FIG. **9B** is a plan view of a mounting board **310** with a plurality of LEDs **900** mounted thereon, according to any of the various embodiments described herein. For ease of illustration, the connectors and contacts, the internal structure of the LED and the phosphor/protective layers are not illustrated. As



shown, the carrier substrate **180'** may be of approximately same size as the LED epi region **110**. In other embodiments, the LED die and the carrier die have sides that are within 100  $\mu\text{m}$  or within about 15% of one another in length. In other embodiments, the LED die and the carrier die have areas that are within 70% of one another, in other embodiments within 85% of one another, and in still other embodiments have same areas. Moreover, a dome or other separate lens need not be provided. Accordingly, packing on the fixture mounting board **310** may be dense.

[0121] In sharp contrast, FIG. **10A** illustrates conventional packing of LED **810** on a carrier substrate **820**, also referred to as a submount, which is in turn mounted on a fixture mounting board **310**. Each LED **800** also includes an associated dome **830** thereon. The submount **820** typically needs to be much bigger than the LED die **810** in order to accommodate the dome thereon. Accordingly, the packing density is generally much lower than may be provided according to various embodiments described herein.

[0122] For example, consider that the LED epi region **110** of FIGS. **9A** and **9B** and the LED die **810** of FIGS. **10A** and **10B** are both about 1.0 $\times$ 1.0 mm in size. The carrier substrate **180'** of FIGS. **9A** and **9B** may be slightly larger, for example about 1.1 $\times$ 1.1 mm in size. Thus, according to various embodiments described herein, the carrier substrate **180'** of FIGS. **9A** and **9B** may be about the same size as the LED epi region **110**. The spacing between adjacent LEDs **900**, shown as "x" in FIGS. **9A** and **9B**, may be about 100  $\mu\text{m}$  in this example. Other LED epi region **110** and die sizes that may be used include 0.5 mm $\times$ 0.5 mm.

[0123] In sharp contrast, in FIGS. **10A** and **10B**, the submount **820** is much larger than the LED die **810**, for example at least about 3 $\times$ 3 mm in size using the same LED die size (about 1.0 $\times$ 1.0 mm) as FIGS. **9A/9B**. This larger size submount **820** is needed to hold the dome **830**. Therefore, the distance "y" between adjacent LED dies **810** may be about 2000  $\mu\text{m}$ , assuming the same submount spacing x. Thus, embodiments of FIGS. **10A-10B** have much lower die packing density on the mounting board **310** than various embodiments described herein, for example in FIGS. **9A** and **9B**. Embodiments of FIGS. **9A** and **9B** can therefore provide for greater light output per unit area of the mounting board **310**.

[0124] A comparison between existing LEDs, as illustrated by LEDs **800** of FIGS. **10A** and **10B**, and LEDs according to various embodiments described herein, as illustrated by LEDs **900** of FIGS. **9A** and **9B**, will now be provided, to quantitatively illustrate the higher optical efficiency that may be provided according to various embodiments described herein.

[0125] Specifically, LEDs **800** of FIGS. **10A** and **10B** may be represented by a Cree® XLamp® XB-D white LED, as described extensively in the Product Family Data Sheet entitled "Cree® XLamp® XB-D White LED", Cree Document No. CLD-DS45 Rev 4, 2011-2012, the disclosure of which is hereby incorporated herein by reference in its entirety as if set forth herein. As described in this Data Sheet, an XB-D LED die **810** may have dimensions of 0.7 mm $\times$ 0.7 mm, or about 0.5 mm<sup>2</sup>. The submount or carrier **820** may have dimensions of 2.45 mm $\times$ 2.45 mm, or about 6 mm<sup>2</sup>. The total height of the XB-D LED may be 1.84 mm, with the total thickness of the carrier being 0.76 mm and the total thickness of the dome **830** being 108  $\mu\text{m}$ . As noted on the first page of the above-cited Product Family Data Sheet, the

XB-D white LED constitutes Cree's smallest lighting class LED, and may produce up to 136 lumens/watt (lm/w) of cool white light at a standard temperature of 85° C. and a standard drive current of 350 mA. Accordingly, on a per-unit area basis, the XB-D LED may produce up to 136 lm/w/(2.45 mm $\times$ 2.45 mm) or about 22 lumens per watt per square millimeter.

[0126] In sharp contrast, various embodiments described herein, as illustrated in FIG. **9A**, may use the same 0.7 mm $\times$ 0.7 mm LED die **110** as the XB-D LED and may use a carrier die **180'** that is also about 0.7 mm $\times$ 0.7 mm in size. As shown in FIG. **11**, various samples of these devices produced between about 105 and about 110 lumens of cool white light (between about 6100 and 6500 K in FIG. **11**) for an average output of about 107 lumens per watt. Thus, an LED according to various embodiments described herein may produce 107 lm/w/(0.7 mm $\times$ 0.7 mm), or at least about 200 lumens per watt per square millimeter. This constitutes an almost tenfold improvement in lumens per watt per square millimeter over the XB-D LED.

[0127] Accordingly, various embodiments described herein may provide a semiconductor LED die **900** that includes an LED epi region **110** and a carrier die **180'** that is electrically connected to the semiconductor LED die **110**, wherein the LED epi region **110** and the carrier die **180'** have sides that are within 100  $\mu\text{m}$  of one another, or within 15% of one another, in length. In some embodiments, the LED epi region **110** and the carrier die **180'** have same side lengths. In other embodiments, the size difference between the LED epi region **110** and the carrier die **180'** of FIG. **9A** may be less than about 100  $\mu\text{m}$ , less than about 200  $\mu\text{m}$ , less than about 500  $\mu\text{m}$ , less than about 10%, less than about 5% and, in various embodiments, may be substantially zero (so that the LED epi region **110** and the carrier substrate **180'** may be about the same size). These relationships may apply to any carrier die and LED die that are smaller, larger or different from various embodiments described herein. In some embodiments, these LEDs can produce at least 45 lumens per watt per square millimeter of, in some embodiments, cool white light (about 6000 K). In other embodiments, these LEDs can produce at least 100 lumens per watt per square millimeter, and in yet other embodiments, these LEDs can produce at least about 200 lumens per watt per square millimeter of, in some embodiments, cool white light (about 6000 K). For warm white light, these values may be decreased by about 30%, so that various embodiments described herein can produce at least 30 lumens of warm white light (about 3000 K) per watt per square millimeter, and in some embodiments, 70 lumens of warm white light per watt per square millimeter, and in yet other embodiments, at least about 140 lumens of warm white light per watt per square millimeter of area of the carrier die.

[0128] The comparative output of the XB-D LED of FIGS. **10A-10B** and LEDs according to various embodiments described herein, may also be provided on a "per volume" (mm<sup>3</sup>) basis. As used herein, "volume" means the product of the area of the carrier die and the total height of the LED, and does not take into account the decreased volume caused by the shape of the dome **830** and/or beveling of the LED die. As described in the above-cited Product Family Data Sheet, the XB-D LED may have a total height of about 1.84 mm, so that its total output per unit volume may be calculated as 136 lm/w/(2.45 mm $\times$ 2.45 mm $\times$ 1.84 mm), or about 12 lumens per watt per cubic millimeter. In

sharp contrast, various embodiments as illustrated in FIGS. 9A and 9B, may have a total height of about 1 mm, so as to produce at least 45 lumens per watt per cubic millimeter of volume of the LED in some embodiments, at least about 100 lumens per watt per cubic millimeter of volume of the LED in other embodiments, and at least about 200 lumens per watt per cubic millimeter of volume of the LED in yet other embodiments, of cool white light. Warm white light values may be decreased by about 30%, to produce at least 30 lumens of warm white light per cubic millimeter of volume of the LED in some embodiments, at least 70 lumens of warm white light per watt per cubic millimeter of volume of the LED in other embodiments, and at least about 140 lumens of warm white light per watt per cubic millimeter of volume of the LED in yet other embodiments.

[0129] As was described above, various embodiments described herein can provide very small LED die/carrier packages compared to, for example, XB-D LEDs described in the above-cited Product Family Data Sheet. As was described above, the XB-D LED has an area of about 2.45 mm $\times$ 2.45 mm or about 6 mm<sup>2</sup>. In contrast, using the same LED die size of 0.7 mm $\times$ 0.7 mm, various embodiments described herein may have area of about 0.5 mm<sup>2</sup>. Other embodiments described herein may use a larger die size and a larger carrier size to produce an area of less than about 1 mm<sup>2</sup>, and yet other embodiments may further increase the die and carrier size to produce an area of less than about 2 mm<sup>2</sup>. Smaller die sizes may also be used. Moreover, the height of various embodiments described herein may be less than about 1.5 mm in other embodiments.

[0130] Other dimensions of various embodiments described herein will now be provided. Specifically, the carrier die 180 may have a thickness of between 50  $\mu$ m and about 100  $\mu$ m, and the LED die (epi region 110 and substrate 120) may have a thickness of between about 100  $\mu$ m and about 1000  $\mu$ m, and in some embodiments may be about 150  $\mu$ m, about 250  $\mu$ m or about 400  $\mu$ m thick, and in some embodiments less than about 500  $\mu$ m thick. A specific embodiment may use a carrier die that is about 100  $\mu$ m thick and an LED die that is about 335  $\mu$ m thick. Specific thicknesses for an LED die that is 240 mm $\times$ 320 mm in area may be about 140  $\mu$ m; for an area of 500 mm $\times$ 500 mm may be about 250  $\mu$ m; for an area of 350 mm $\times$ 470 mm may be about 155  $\mu$ m; for an area of about 700 mm $\times$ 700 mm, 850 mm $\times$ 850 mm, 1000 mm by 1000 mm or 1400 mm $\times$ 1400 mm may be about 355  $\mu$ m. Moreover, commercially available sapphire die may be between 85  $\mu$ m and about 150  $\mu$ m thick, and typically less than about 200  $\mu$ m thick. A phosphor coating may be added in some embodiments, which may have a thickness of less than about 1 mm in some embodiments, between 10  $\mu$ m and 500  $\mu$ m in other embodiments, and in yet other embodiments between about 20  $\mu$ m and about 60  $\mu$ m.

[0131] Accordingly, an LED according to various embodiments described herein may comprise a semiconductor LED die that includes an LED epi region and a carrier die that is electrically connected to the LED die, wherein the LED epi region and the carrier die have sides that are within 100  $\mu$ m of one another in length and, in some embodiments, have the same side lengths. Moreover, these LEDs may be combined with a light fixture mounting board on which the LED die is mounted and a light fixture housing in which the light fixture mounting board is mounted to provide a light fixture,

wherein the light fixture is free of a dome between the LED die and the light fixture housing.

[0132] Other embodiments may provide an LED light fixture that includes a light fixture mounting board, a plurality of LEDs mounted on the light fixture mounting board, and a light fixture housing in which the light fixture mounting board including the plurality of LEDs thereon is mounted. The light fixture is free of a dome between a respective LED and the light fixture housing.

[0133] FIGS. 12-16 provide photographs of prototype LEDs according to various embodiments described herein. These figures are provided to highlight the scale and/dimensional relationships between the various features of the prototype LEDs, such as the carrier, the epi region, the primary optic and the phosphor layer, according to various embodiments described herein. Specifically, FIG. 12A, is a side photograph, FIG. 12B is a bottom photograph, FIG. 12C is another side photograph and FIGS. 12D and 12E are top photographs of a prototype LED according to various embodiments described herein. FIG. 13A provides a more detailed bottom photograph, and FIG. 13B provides a more detailed top photograph. FIG. 13C provides a side photograph with dimensions, based on a carrier die and substrate die that are 0.7 mm $\times$ 0.7 mm in size.

[0134] FIG. 14 provides photographs of a wafer after singulation, a prototype LED component, a backside contact and a prototype LED under bias. FIG. 15 illustrates relative sizes of various LEDs, such as XM-L high voltage, XT-E and XB-D LEDs available from the assignee, Cree, Inc. wherein a 0.7 mm $\times$ 0.7 mm LED according to various embodiments described herein is illustrated at the far right and is labeled "WLP". Finally, FIG. 16 provides photographs of an LED according to various embodiments described herein after die separation, and when mounted on a mounting board and installed in a fixture.

[0135] Accordingly, various embodiments described herein can move testing and singulation to the very end of the wafer level processing. Production efficiency and/or luminous efficiency may thereby be improved.

#### Wafer Level Packaging of Multiple LEDs on a Single Carrier Die

[0136] Wafer level packaging of multiple LED chips on a single carrier die according to various embodiments will now be described. Specifically, various embodiments described above in connection with FIGS. 1A-16 provided a one-to-one correspondence among the LED dies on the LED wafer and the carrier dies on the carrier wafer, so that after singulation, a single LED die is joined to a respective carrier die. In contrast, various embodiments that will now be described in connection with FIGS. 17-36 may arise from a recognition that it may be desirable to join a plurality of LED dies to a single carrier die using wafer level packaging techniques that were described above. The multiple LED dies may be connected on the single carrier die in series and/or in parallel, to provide an LED chip. By connecting a plurality of LED dies on a single LED chip in series, a higher voltage LED chip may be provided. Moreover, by connecting a plurality of LED chips in parallel on a single carrier die, a higher current LED chip may be provided. Other potential advantages in terms of cost and/or performance may be obtained by providing a plurality of LED dies that are electrically connected in series and/or in parallel on a single carrier die.

[0137] FIG. 17 is a cross-sectional view of an LED chip according to various embodiments described herein. Referring to FIG. 17, the LED chip 1700 includes a plurality of LED dies 110', a respective one of which includes an anode contact 160 and a cathode contact 170 on a face thereof. The LED dies 110' may be fabricated and configured according to any of the embodiments described in connection with FIGS. 1A-16. A carrier die 180' includes a first face 182a and a second face 182b. A plurality of internal contacts 1710 are provided on the first face 182a, that are configured to electrically connect the anode and cathode contacts 160 and 170, respectively, of the plurality of LED dies 110', in series and/or in parallel, when the carrier die 180' is electrically connected to plurality of LED dies 110'. The carrier die 180' also includes an external anode contact 192 and an external cathode contact 194 on the second face 182b. The external anode and cathode contacts 192, 194 may be connected to separate ones of the internal contacts 1710 using a plurality of vias 196. Moreover, in any of the embodiments described herein, the contacts that are configured to electrically connect the anode and cathode contacts of a plurality of LED dies in series and/or in parallel may be provided internal to the carrier die 180', in addition to or instead of on a face thereof, using techniques that may be similar to those used for multilayer wiring substrates or multilayer printed circuit boards having internal wiring layers.

[0138] Still referring to FIG. 17, the plurality of LED dies 110' and the carrier die 180' are joined or connected to one another, so that the anode and cathode contacts 160, 170, respectively, of the LED dies 110' are adjacent the first face 182a of the carrier die 180' and the plurality of internal contacts 1710 on the first face 182a electrically connect the anode and cathode contacts 160, 170 of the plurality of LED dies 110' in series and/or in parallel. Various connection configurations will be described below in connection with FIGS. 28A-28C.

[0139] The LED dies 110' and the carrier die 180' may be embodied according to any of the embodiments that were described in connection with FIGS. 1A-16. For example, the LED dies 110' may be fabricated from an LED wafer 100, as was described in any of the embodiments described in connection with FIGS. 1A-16. Moreover, the carrier die 180' may be fabricated from a carrier wafer 180 according to any of the embodiments described in connection with FIGS. 1A-16, except that the anode pads 184 and cathode pads 186 may be replaced by the plurality of internal contacts 1710.

[0140] Accordingly, embodiments of FIG. 17 may be regarded as providing a submount 180' with traces 1710 on the top side 182a for mounting LED dies 110' in series, and a single anode 192 and cathode 194 on the backside for each string of LEDs 110'. Dies 110' may be mounted at the wafer level, and singulated to a component, as shown in FIG. 17. The submount 180' may be cut as a high aspect ratio rectangle, where, for example, a single row of dies 110' is mounted end-to-end in a linear fashion. However, the submount may be other shapes, such as a square submount, as will be described below. An oxide film may also be provided under the top side pads, to reduce submount leakage.

[0141] FIG. 36 is a flowchart of operations that may be performed to manufacture an LED chip, such as the LED chip 1700 of FIG. 17, according to various embodiments described herein. Referring to FIG. 17, at Block 3610, an LED wafer that includes a plurality of LED dies is provided. The plurality of LED dies include anode and cathode

contacts on a face thereof. The LED wafers may be embodied by LED wafers 100, according to any of the embodiments described in connection with FIGS. 1A-16.

[0142] At Block 3620, a carrier wafer is provided. The carrier wafer includes first and second opposing faces and a plurality of internal contacts on the first face that are configured to electrically connect the anode and cathode contacts of at least two of the LED dies in series and/or in parallel when the carrier wafer is joined to the LED wafer. The carrier wafer also includes at least one external anode contact and at least one external cathode contact on the second face. A carrier wafer 180 according to any of the embodiments described in connection with FIGS. 1A-16 may be used, except that the internal contact structure is modified to provide the series/parallel connections.

[0143] Still referring to FIG. 36, at Block 3630, the LED wafer and the carrier wafer are joined, so that the anode and cathode contacts of the LED dies are adjacent the first face of the carrier wafer and the plurality of internal contacts on the first face electrically connect the anode and cathode contacts of the at least two of the LED dies in series and/or in parallel. Wafer joining may take place using any of the techniques that were described above in connection with FIGS. 1A-16.

[0144] Still referring to FIG. 36, at Block 3640, the LED wafer and the carrier wafer that have been joined are singulated to provide a plurality of LED chips, a respective one of which includes a single carrier die, wherein a respective single carrier die includes a plurality of LED dies thereon that are electrically connected in series and/or in parallel. Any of the singulating techniques described above in connection with FIGS. 1A-16 may be used, provided that, after singulation, a single carrier die includes multiple LED dies thereon that are connected in series and/or in parallel. It will be understood that singulation may be performed using multiple operations. For example, a first singulation operation may singulate the LED dies from one another in the LED wafer, and a second singulation operation may singulate the individual carrier dies in the carrier wafer. In other embodiments, the individual LED dies for a single carrier die need not be singulated, and a single singulation operation may be used to singulate the carrier wafers and the plurality of LED chips that are associated with the single carrier wafers.

[0145] Still referring to FIG. 36, between the joining (Block 3630) and the singulating (Block 3640), various scribing, substrate shaping, phosphor applying, electrical/optical testing, inspection, binning and/or sorting operations may take place as was described in connection with FIGS. 1A-16 above. Moreover, after singulating at Block 3640, various packaging and/or fixture manufacturing operations may also take place, as was described above in connection with FIGS. 1A-16. It will be understood that any of the embodiments described above in connection with FIGS. 1A-16 may be used in connection with wafer level packaging of multiple LED dies on a single carrier die according to various embodiments described herein. For example, the LED dies 110' may include an LED epi region on an LED substrate, as was described above in connection with FIGS. 1A-16. As was also described in connection with FIGS. 1A-16, at least a portion of the LED substrate may be removed. As was also described in connection with FIGS. 1A-16, a respective LED die 110' may include a sidewall, at least a portion of which is oblique to the face of the LED die.

Moreover, the carrier die **180'** may comprise silicon. Various other embodiments will now be described.

**[0146]** FIG. 18 illustrates other embodiments, wherein a face of a respective LED die **110'** that is opposite the anode and cathode contacts **160, 170** includes a textured surface **112**, as was described above in connection with FIGS. 1A-16. Other shaping operations may be performed, as was described above in connection with FIGS. 1A-16. The shaping may be performed between the joining and singulating operations (Blocks **3630** and **3640** of FIG. 36).

**[0147]** Still referring to FIG. 18, a face of a respective LED **110'** that is opposite the anode and cathode contacts **160, 170** includes a wavelength conversion material **220** thereon, according to any of the embodiments that were described above in connection with FIGS. 1A-16. The wavelength conversion material **220** may be applied between the joining and the singulating operations as was described above in connection with FIGS. 1A-16. The wavelength conversion material **220** may also be applied after singulating, for example using spraying and/or other deposition techniques, so that the wavelength conversion material can also cover portions of the carrier die **180'** that do not have an LED die **110'** thereon. As also shown in FIG. 18, both texturing **212** and wavelength conversion material **220** may be used, in some embodiments. Moreover, as was described above in connection with FIGS. 1A-16, the sidewalls of the LED dies **110'** may also include texturing and/or a wavelength conversion material thereon and may be fabricated as was described in connection with FIGS. 1A-16.

**[0148]** Referring to FIG. 19, a protective material **222** may also be provided on a face of a respective LED die **110'** that is opposite the anode and cathode contacts **160, 170**. The protective material **222** may be applied at the wafer level, according to any of the embodiments that were described above in connection with FIGS. 1A-16, and may also be applied to the sidewalls of the LED dies, according to any of the embodiments that were described above in connection with FIGS. 1A-16. Various combinations and subcombinations of texturing **212**, wavelength conversion material **220**, and protective material **222** may be provided. In some embodiments, the wavelength conversion material **220** comprises silicon having phosphor particles therein, and the protective material **222** may comprise the silicon without the phosphor particles therein.

**[0149]** FIG. 20 illustrates a relatively thick protective layer **222'** that may also provide a primary optic for the LED as described, for example, in U.S. patent application Ser. No. 13/649,052 to Lowes et al., filed Oct. 10, 2012, entitled "LED Package With Encapsulant Having Planar Surfaces", the disclosure of which is incorporated herein by reference as if set forth fully herein. Accordingly, the protective layer **222, 222'** can provide optical, encapsulation and/or other properties.

**[0150]** FIG. 21 illustrates other embodiments wherein a dome **2100** is provided that extends from the first face of the carrier die **180'** across the plurality of LED dies **110'**. The dome **2100** may be molded or formed using any conventional techniques. The dome may include phosphor particles therein and/or thereon in a uniform or nonuniform composition and/or concentration.

**[0151]** FIG. 22 illustrates other embodiments that further include a mounting substrate **2210** on the carrier die **180'**, remote from the plurality of LED dies **110**, and a dome **2200** that extends from a face of the mounting substrate **2210**

across the carrier die **180'** and across the plurality of LED dies **110'**. The dome **2200** may be molded or formed using any conventional techniques. The dome may include phosphor particles therein and/or thereon in a uniform or non-uniform composition and/or concentration.

**[0152]** FIG. 23 illustrates other embodiments wherein a layer **2300** of wavelength conversion material such as phosphor is provided that is remote from the plurality of LED dies **110'**. A housing or standoff **2310** may be used to maintain the wavelength conversion layer **2300** remote from the plurality of LED dies **110'**. The wavelength conversion layer **2300** may include a binder, such as a silicone binder including phosphor particles therein and/or thereon in a uniform or nonuniform composition and/or concentration. Air, other gas and/or other transparent material may be provided in the space between the wavelength conversion layer **2300** and the LED dies **110'**.

**[0153]** FIG. 24 illustrates other embodiments wherein the carrier die **180'** further comprises at least one external thermal contact **2400** on the second face **182b** that is not electrically connected to the external anode contact **192** or to the external cathode contact **194**. In FIG. 24, three external thermal contacts **2400** are provided.

**[0154]** FIG. 25 illustrates other embodiments wherein a plurality of domes **2510** are provided, a respective one of which is on a respective LED die **110'** remote from the anode and cathode contacts **160, 170** thereof. The individual domes may be formed using dispensing, overmolding, drop coating and/or other techniques. The dome **2510** may be molded or formed using any conventional techniques. The dome may include phosphor particles therein and/or thereon in a uniform or nonuniform composition and/or concentration.

**[0155]** FIG. 26 illustrates a plurality of lenses **2610** on a respective LED die **110'**. The plurality of lenses **2610** may be macro lenses having a dimension (such as height, width, diameter, etc.) of at least about 100  $\mu\text{m}$  and/or microlenses having a dimension that is less than about 100  $\mu\text{m}$ . The lenses **2610** need not be hemispherical, and may be identically or differently shaped and/or sized. The lenses can be fabricated from spin-on glass, BCB, transfer molding or photolithography, and may include phosphor therein and/or thereon.

**[0156]** FIG. 27 illustrates an LED chip **1700** according to any of the embodiments described in connection with FIGS. 17-26 and 28A-36, installed in a light fixture housing **330** to provide a light fixture **340**. As was described above in connection with FIG. 2, the light fixture housing **330** may include opaque/reflective portions **330a** and transparent portions **330b**, to allow light to emerge from the housing. A separate light fixture mounting board may be provided, as was described in connection with element **310** of FIG. 2, or the LED chip **1700** may be mounted directly in the housing **330** without the need for a light fixture mounting board. In some embodiments, the housing **340** is a vehicle headlight or taillight housing. The overall fixture **340** may be cheaper and/or more efficient, since the driver may be higher voltage when a string of series connected LED dies **110'** is provided.

**[0157]** FIGS. 28A-28C illustrate various configurations of LED dies **110'** on a carrier die **180'** according to various embodiments described herein. For example, in FIG. 28A, a single row of the LED dies **110'** is connected in series by the internal contacts **1710**, represented by arrows in FIG. 28A. Thus, in FIG. 28A, the carrier die **180'** may be an elongated (high aspect ratio) rectangle, such as may be used in vehicle

headlights/taillights. The string can provide an LED filament for a fixture. More than one row of LED dies may be provided, and any number of LED dies greater than one may be provided.

[0158] In contrast, in FIG. 28B, the carrier die 180' is square shaped, and may include a series connection of, for example, nine (9) LED dies 110'. Fewer or more LED dies 110' may be used, and rectangular or other shaped carrier dies 180' (including circular) may be used. Moreover, in FIG. 28C, nine LED dies 110' may be connected in three parallel strings of three LED dies.

[0159] In some embodiments of FIGS. 28B and 28C, the carrier die 180' may have the same dimensions of a Cree® XLamp® XP-E high efficiency white LED, that is described in the data sheet "Cree® XLamp® XP-E High Efficiency White LEDs", Cree Data Sheet No. CLD-DS34 Rev 3A, 2010-2012, the disclosure of which is hereby incorporated herein by reference in its entirety as if set forth herein. More specifically, in some embodiments of FIGS. 28B and 28C, the carrier die 180' may be 3.45 mm×3.45 mm in size, to provide the same external footprint as a Cree XLamp XP-E high efficiency white LED, but may include multiple LED dies connected in series (FIG. 28B) or in series/parallel (FIG. 28C).

[0160] Other configurations are also possible. For example, embodiments of FIG. 28B may include a single external anode contact and a single external cathode contact on the backside. Embodiments of FIG. 28C may also include a single external anode and cathode contact on the backside that connects the three series strings of three LED dies in parallel, or may include three pairs of external anode/cathode contacts on the backside, to provide three separate sets of series strings. Various other combinations/subcombinations of series and parallel connections may be provided. Moreover, larger or smaller footprints may be provided.

[0161] In some embodiments, the number of LED dies in each string may be a function of a desired voltage for the LED chip. For example, if one LED die 110' has a forward voltage of about 3V, then the forward voltage of the LED chip of FIG. 28B may be about 27V, and the forward voltage of the LED chip of FIG. 28C may be about 9V. Strings of four LEDs may also be provided, for example as was illustrated in FIG. 28A, to provide a 12V device, which may be particularly useful in vehicular applications.

[0162] FIGS. 29A-29C illustrate other embodiments wherein an LED chip 1700 according to any of the embodiments described herein may be placed in a Cree XLamp XP-E high efficiency white LED package in place of a single LED die.

[0163] FIGS. 30A-30C illustrate various configurations of texturing 212, wavelength conversion layers 220 and protective layers 222 that were generally illustrated in FIGS. 19 and 20. Various thicknesses of the protective layer 222, 222', 222" may provide primary optics having different characteristics, as described, for example, in the above cited U.S. patent application Ser. No. 13/649,052.

[0164] FIG. 31 illustrates a top view of lenses 2610, which may be macrolenses and/or microlenses, as was described above in connection with FIG. 26. FIG. 32 illustrates a dome 2510 on an LED die 110', as was described above in connection with FIG. 25.

[0165] FIG. 33 illustrates the mechanical dimensions of a Cree XLamp XP-E high efficiency white LED including the

recommended PCB solder pad and recommended stencil pattern therefor. As was described above, an LED chip 1700 according to any of the embodiments described herein may be placed in a Cree XLamp XP-E high efficiency white LED package in place of a single LED die.

[0166] FIG. 34 is a bottom view of a carrier die 180' according to various other embodiments described herein. As shown in FIG. 34, the carrier die 180' includes an external anode contact 192, an external cathode contact 194, and a plurality of external thermal contacts 2300 that are not electrically connected to the external anode contact 192 or the external cathode contact 194. It is known to provide multiple bond pads for an LED, as described, for example, in U.S. Patent Application Publication 2012/0217530 to Edmond et al., entitled "Semiconductor Light Emitting Diodes Having Multiple Bond Pads and Current Spreading Structures", the disclosure of which is hereby incorporated herein by reference. Moreover, the Cree XLamp XP-E device that was described above also includes a single external thermal contact. However, various embodiments of FIG. 34 can provide a plurality of external thermal contacts 2300. An external thermal contact 2300 may also be referred to as a "neutral contact" or as a "neutral thermal contact".

[0167] The plurality of external thermal contacts 2300 of FIG. 34 may also be used in other LEDs, such as a Cree XLamp XP-E high efficiency white LED, or in any of the embodiments that were described above in connection with FIGS. 1A-16, to provide multiple external thermal contacts.

[0168] FIG. 35 is a top view of an LED chip of FIG. 17, illustrating the plurality of internal contacts 1710, the plurality of LED dies 110' and a link or strap 3510 that electrically connects non-adjacent LED dies 110'. Various configurations of links or straps 3510 may be provided to electrically connect adjacent and/or non-adjacent LED dies in a desired series/parallel circuit. In some embodiments, the link or strap 3510 may be a thin strap, for example about 20 μm wide, of conductive material.

[0169] It will be understood that various embodiments of FIGS. 17-36 may also be combined with various embodiments of FIGS. 1A-16. For example, the various protective layers 222, 222', 222" that were illustrated in FIGS. 19, 20 and 30A-30C, may be incorporated into embodiments of FIGS. 1A-16. Moreover, an individual dome 2510, as was illustrated in FIGS. 25 and 32, may also be incorporated into any of the embodiments of FIGS. 1A-16. In addition, macro- and/or microlenses 2610, as were illustrated in FIGS. 26 and 31, may also be incorporated into any of the embodiments of FIGS. 1A-16. Thus, various lenses in the form of a cube, a dome, an overmold and/or a microlens may be provided in any of the embodiments described herein. Finally, any of the internal structures or manufacturing techniques of FIGS. 1A-16 may be incorporated into embodiments of FIGS. 17-36. For example, the internal structure of an LED die 110/110', the internal interconnection structures 180a, the substrate shaping, singulation, wavelength conversion layer configuration and LED fabrication, chip fabrication and module/fixture fabrication of FIGS. 1A-16 may also be incorporated into embodiments of FIGS. 17-36.

Additional Wafer Level Packaging of Multiple LEDs on a Single Carrier Die

[0170] Wafer level packaging of multiple LED dies on a single carrier die according to various embodiments that were described in connection with FIGS. 17-36 used wiring

in and/or on the carrier die to electrically connect the LED dies in series and/or in parallel, to provide an LED chip. Additional embodiments that will now be described in connection with FIGS. 37-53 can provide other embodiments of wafer level packaging of multiple LED dies on a single carrier die, where a patterned internal interconnection layer in the plurality of LED dies themselves may be used to connect the plurality of LED dies in series and/or in parallel. Thus, interconnection may be provided by the LED substrate instead of or in addition to the carrier wafer.

[0171] Various embodiments that will now be described may arise from a recognition that a patterned internal interconnection layer may be provided in an LED die for other purposes, such as to provide a crack-tolerant barrier structure, as described in U.S. patent application Ser. No. 13/790,369, to Donofrio et al., filed Mar. 8, 2013, entitled Semiconductor Light Emitting Diodes With Crack-Tolerant Barrier Structures and Methods of Fabricating Same, assigned to the assignee of the present application, the disclosure of which is hereby incorporated herein by reference in its entirety as if set forth fully herein. Various embodiments that will now be described can selectively extend the patterned internal interconnection layer between adjacent LED dies in order to selectively electrically interconnect the LED dies in series and/or in parallel.

[0172] In more detail, FIG. 37 is a reproduction of FIG. 9 of the above incorporated application Ser. No. 13/790,369. As shown in FIG. 37, an LED chip structure 100D includes a "crack reducing interlayer" 145. A portion 145A of the crack reducing interlayer 145 contacts the anode bond pad 160, while a portion 145B of the crack reducing interlayer 145 contacts the cathode bond pad 170 and/or a reflective cathode contact 150. Thus, where the crack reducing interlayer 145 includes a conductive material such as aluminum, one or both of the portions 145A, 145B of the crack reducing interlayer 145 may be electrically active. However, as the portions 145A, 145B of the crack reducing interlayer 145 are isolated from one another by a gap or moat 146, such contact will not cause a short circuit. Various embodiments that will now be described can selectively extend the conductive interlayer 145 across adjacent LED dies on an LED substrate, so as to selectively electrically connect the anodes and cathodes of the LED dies in series and/or in parallel. The patterned internal interconnection layer 145 may also provide functionality of a crack reducing interlayer and/or other functionality.

[0173] FIG. 38 illustrates an LED chip according to various embodiments described herein. FIG. 38, which selectively electrically connects the anodes and cathodes of a plurality of LED dies in series and/or in parallel in the LED dies themselves, may be contrasted with FIG. 17, wherein the anodes and/or cathodes of the plurality of LED dies are electrically connected in series and/or in parallel using internal contacts in and/or on a carrier die. It will also be understood that any of the embodiments of FIGS. 17-36 may be combined with any of the embodiments of FIGS. 37-53, to provide interconnections that use the LED dies and the carrier die.

[0174] More specifically, referring to FIG. 38, an LED chip includes an LED substrate 3800 having a plurality of LED dies 3810 (shown as three LED dies 3810a-3810c in FIG. 38). A respective LED die 3810 includes an anode and a cathode (which will be illustrated in subsequent figures). A patterned internal interconnection layer 145C is provided

in the plurality of LED dies 3810, and as shown in FIG. 38, in the LED epi region 110. The patterned internal interconnection layer 145C is configured to selectively electrically connect the anodes and cathodes of the plurality of LED dies 3800 in series and/or in parallel. An LED die anode contact 160a is electrically connected to at least one of the anodes, and an LED die cathode contact 170a is electrically connected to at least one of the cathodes. The internal structure of the LED epi region 110 will be illustrated in subsequent figures. As will also be described, the patterned internal interconnection layer 145C may be part of a crack reducing interlayer 145 in some embodiments.

[0175] Thus, the patterned internal interconnection layer 145C may comprise a patterned internal metal layer that selectively extends between the plurality of LED dies 3810, to selectively electrically connect the anodes and cathodes of the plurality of LED dies 3810 in series and/or in parallel.

[0176] Still referring to FIG. 38, the LED chip includes a carrier die 180' having first and second opposing faces 182a and 182b, respectively. The carrier die 180' has a first anode contact 1710a and a first cathode contact 1710b on the first face 182a, and a second anode contact 192 and a second cathode contact 194 on the second face 182b. The carrier die 180' is joined to the LED substrate 3800 so that the plurality of LED dies 3800 are adjacent the first face 182a and is joined to the LED substrate 3800 so that the plurality of LED dies 3810, and in some embodiments the LED epi region 110, are adjacent the first face 182a, the first anode contact 1710a is electrically connected to the LED die anode contact 160a, and the first cathode contact 1710b is electrically connected to the LED die cathode contact 170a. The remaining LED die anode and cathode contacts 160 and 170 may be electrically connected to neutral or thermal contacts 2300 and/or may be unconnected. A single thermal contact 2300 also may be provided. Moreover, one or more thermal contacts 2300 may be provided on the second face 182b, in addition to or instead of on the first face 182a of the carrier die 180'. The thermal contacts are not connected to the anodes or cathodes in some embodiments.

[0177] As also shown in FIG. 38, the LED substrate 3800 may include beveled sidewalls between adjacent ones of the LED dies 3810, and a beveled edge at a periphery thereof. A wavelength conversion material 220 may be provided on the LED substrate 3800 remote from the carrier substrate 180', and extending onto the beveled sidewalls between adjacent ones of the LED dies 3810, onto the beveled edge of the periphery of the LED substrate 3800, and also extending onto a sidewall of the LED dies 3810a, 3810c at the periphery of the LED substrate 3800 (i.e., on an exposed edge of the LED epi region 110).

[0178] Various techniques of LED substrate shaping including texturing, microlensing and/or beveling that were described in connection with the other embodiments herein, as well as various embodiments of a mounting substrate and/or a light fixture housing, may be used in the present embodiments.

[0179] Finally, in some embodiments, the carrier die 180' may include a passivated reflector 3820 on or adjacent the first face 182a. The passivated reflector 3820 may include a reflector metal, such as aluminum, having a dielectric passivation layer, such as silicon dioxide and/or silicon nitride on opposite faces thereof. The passivated reflector 3820 may be provided in, adjacent and/or on the first face 182a of any of the carrier dies 180' according to any of the embodiments

described herein, and may be fabricated using techniques that will be described below. Other embodiments of a reflector **3820** may be provided. For example, a reflector may be embodied as a hybrid mirror, as is described, for example, relative to FIG. **54** below. In yet other embodiments, a reflector **3820** may be formed only of dielectric material having, for example, differing indices of refraction. For example, a distributed Bragg reflector may be used.

[0180] FIGS. **39-49** are cross-sectional views illustrating methods of fabricating a plurality of LED chips, such as the LED chips of FIG. **38**, according to various embodiments described herein, and various intermediate and final products according to various embodiments described herein. Referring to FIG. **39**, an LED wafer **3910** is provided that includes a plurality of LED dies **3920a-3920d**. It will be understood that only four LED dies **3920a-3920d** are illustrated in FIG. **39**. Typically, however, many more dies **3920** are included in an LED wafer **3910**. Moreover, for purposes of explanation, assume that LED dies **3920a** and **3920b** will be connected in series on the LED wafer **3810**, LED dies **3920c** and **3920d** will be connected in series on the LED wafer **3910**, but LED dies **3920b** and **3920c** will not be connected to one another. Stated differently, LED dies **3920a** and **3920b** will eventually form a first LED chip having series connected LED dies, and LED dies **3920c** and **3920d** will form a second LED chip having LED dies that are connected in series. The LED wafer **3910** includes a substrate **120**, such as a silicon carbide substrate, one or more n-type layers **112** (also referred to as a “cathode”), an active region, and one or more p-type layers **114** (also referred to as an “anode”), according to any of the embodiments described herein. For convenience, the active region will not be shown, but it will be understood that an active region will generally be present between the n-type layers **112** and the p-type layers **114**. A patterned layer **130** of reflective material, such as a silver or nickel layer, is provided on the p-type layers **114**, to provide a reflective anode contact. A barrier layer **132** of, for example, titanium tungsten, tungsten, platinum and/or other suitable material, is formed on the reflective anode contact **130** and patterned as shown in FIG. **39**.

[0181] Referring to FIG. **40**, trenches are etched between the LED dies that will be connected together. For example, as shown, a trench **4010** is formed between dies **3920a** and **3920b** and between dies **3920c** and **3920d**. These trenches **4010**, which may be referred to herein as “first trenches”, are etched sufficiently deep to penetrate through the n-type layer **112**, so as to isolate adjacent LED dies **3920** from one another. They may extend up to the substrate **120** or may penetrate into the substrate **120** as shown.

[0182] Then, referring to FIG. **41**, a base or first insulating layer **140A** may be blanket-deposited over the structure to cover the exposed portion of the anode contacts **130** and the barrier layer **132**. The first insulating layer **140A** may extend into the trenches **1410** and onto the exposed portions of the p-type layers **114**, the active layers and the n-type layers **112**. The first insulating layer **140A** may include a dielectric material, such as silicon dioxide and/or silicon nitride, and may have a thickness of between about 250 nm and 1  $\mu\text{m}$ , and in particular embodiments, may comprise about 500 nm of silicon nitride.

[0183] Referring now to FIG. **42**, an internal interconnection layer **145** is then deposited on the first insulating layer **140A** and patterned, as shown in FIG. **42**. The internal

interconnection layer **145** may comprise any conductor. For example, a metal such as aluminum, titanium, tungsten, aluminum/titanium, aluminum/titanium/tungsten, titanium/tungsten and/or other metal(s) may be used. In some embodiments, the internal interconnection layer **145** may have a thickness of about 150 nm. In some embodiments, the internal interconnection layer **145** may be sufficiently thin so as to be transparent, but sufficiently thick so as to be conductive. In other embodiments, the internal interconnection layer **145** may be sufficiently thick so as to not be optically transparent and may, in fact, be optically absorbing. In other embodiments, the internal interconnection layer **145** may be reflecting. The fabrication details of metal layers in an LED that are reflective, transparent or absorbing need not be described further herein.

[0184] As shown in FIG. **42**, the internal interconnection layer **145** is patterned so as to leave a gap or moat **146** that separates the layer into two separate portions, as will be discussed in detail below. Moreover, as shown in FIG. **42**, the internal interconnection layer **145** extends across the trench **4010** between the LED dies **3920a** and **3920b** that are to be interconnected and also extends between trench **4010** between the LED dies **3920c** and **3920d** that are to be interconnected. Thus, by extending across the trenches **4010**, series or parallel connections between adjacent LED dies may be provided. On the other hand, the gap **146** can prevent short circuiting of a given LED die's anode and cathode to one another. As also shown in FIG. **42**, the interconnection layer **145** does not extend between adjacent LED dies that are not to be interconnected. Thus, the interconnection layer **145** does not extend between LEDs **3920b** and **3920c**. In other embodiments, however, the interconnection layer **145** may extend between these dies and may be removed later.

[0185] Referring now to FIG. **43**, an upper or second insulating layer **140B** may be blanket-deposited over the structure. The second insulating layer **140B** may have the same composition or a different composition as the first insulating layer **140A**. The second insulating layer **140B** may include a dielectric material, such as silicon nitride and/or silicon dioxide, and may have a thickness of between about 250 nm and about 1  $\mu\text{m}$ . In some embodiments, the second insulating layer **140B** may include silicon nitride and may have a thickness of about 500 nm. In other embodiments, the second insulating layer **140B** may comprise about 5,000 Å silicon nitride and about 2,000 Å silicon dioxide.

[0186] Referring now to FIG. **44**, the insulating layer **140**, which comprises the first insulating layer **140A** and the second insulating layer **140B**, and the internal interconnection layer **145** may be etched to open vias therein that extend to the barrier layer **132** and to the n-type layer **112**. Two different etching operations may be used or a single or overlapping etching operations may be performed. A reflective cathode contact **150** and a cathode bond pad **170** are formed to contact the n-type layer **112** and an anode bond pad **160** is formed to contact the barrier layer **132**. Additional layers, such as reflective, adhesive or bonding layers, may also be included. The cathode bond pad **170** may also be referred to as a “cathode contact” and the anode bond pad **160** may also be referred to as an “anode contact”.

[0187] Still referring to FIG. **44**, it can be seen that the patterned internal interconnection layer **145** now includes three separate portions. A first portion **145A** is electrically connected to the anode bond pads **160**. A second portion

**145B** is connected to the cathode bond pads **170**, but is spaced apart from the first portion **145A** by the gaps **146**. Thus, a given LED die is not shorted. A third portion **145C** extends between an anode bond pad **160** and a cathode bond pad **170** of two adjacent LEDs, to connect these LEDs in series and/or in parallel. Thus, for example, the third portion **145C** connects the anode bond pad **160** of LED die **3920b** to the cathode bond pad **170** of the LED die **3920a**.

[0188] Referring now to FIG. 45, second trenches **4510** are etched to define groups of LED dies **3920** that are not electrically interconnected. For example, as shown in FIG. 45, a second trench **4510** is etched between LED dies **3920b** and **3920c**. The second trench **4510** extends through the n-type layer into the substrate **120**. As also shown, the second trenches **4510** are deeper than the first trenches **4010**. Moreover, in embodiments wherein the patterned internal interconnection layer **145** spans across LED dies **3920b** and **3920c**, this patterned internal interconnection layer between these dies can be removed when etching the second trenches **4510**, thus electrically isolating the groups of LED dies that will not be electrically connected in series and/or in parallel.

[0189] Accordingly, FIG. 45 illustrates providing an LED wafer **3910** that includes a plurality of LED dies **3920a-3920d**, a respective LED die including an anode **160** and a cathode **170**. The LED wafer **3910** further includes a patterned internal interconnection layer **145** in the plurality of LED dies **3920** that is configured to selectively electrically connect the respective anodes **160** and cathodes **170** of at least two of the LED dies **3920a**, **3920b** and **3920c**, **3920d**, in series and/or parallel. The LED wafer **3910** further includes a plurality of external anode contacts **160a** (also referred to herein as “LED die anode contacts **160a**”) and a plurality of external cathode contacts **170a** (also referred to herein as “LED die cathode contacts **170a**”), a respective pair of which is configured to provide an external anode contact and an external cathode contact for a respective at least two of the LED dies that are connected in series and/or in parallel.

[0190] In some embodiments, the first trenches **4010** of FIG. 40 may be etched using chlorine-based Reactive Ion Etching (RIE), and the second trenches **4510** of FIG. 45 may be etched using Inductively Coupled Plasma Reactive Ion Etching (ICP-RIE), typically fluorine-based in the case of etching into the SiC substrate. ICP etching typically has a much higher etch rate than standard RIE etching. Moreover, for comparison purposes, the depth of second trenches **4510** into the substrate **120** may be about 10-50  $\mu\text{m}$  in some embodiments, whereas the depth of first trenches **4010** in these same embodiments may be about 0-1  $\mu\text{m}$ .

[0191] It will be understood that various other embodiments of FIG. 45 may be provided. For example, the anode contacts **160** and the cathode contacts **170** that will not form an external anode contact **160a** or an external cathode contact **170a** may be omitted, may be of a different shape, or may not be brought to the surface of the LED wafer **3910**. Alternatively, the anode contacts **160** and the cathode contacts **170** that do not form external anode contacts **160a** or external cathode contacts **170a** may be provided in a two-piece form, wherein a lower piece electrically contacts the first or second portion **145a** or **145b** of the patterned internal interconnection layer **145**, and a second portion, at the surface of the LED wafer **3910**, is insulated from the first portion, and is provided for thermal and/or mechanical support purposes. When provided for thermal purposes, a

single thermal contact may be provided by the second pieces of the anode and cathode contacts **160**, **170**, as long as the thermal contact does not electrically connect the anode and cathode of a device. Various other configurations may be provided.

[0192] Referring now to FIG. 46, a carrier wafer **180** is fabricated according to any of the embodiments described herein. In FIG. 46, the carrier wafer **180** includes first and second opposing faces **182a** and **182b**, a plurality of first anode contacts **1710a** on the first face **182a** and a plurality of second anode contacts **1710b** on the second face **182b**. In these embodiments, the carrier wafer **180** may also include at least one external thermal contact **2300** on the first face **182a** and/or on the second face **182b**. The external thermal contacts **2300** may be connected by internal metal vias for thermal transfer purposes, but need not be connected by internal metal vias in other embodiments.

[0193] Optionally, the carrier wafer **180** also includes a passivated reflector **3810** on the first face **182a**. The passivated reflector may include a first insulating layer **3812**, which may comprise silicon dioxide and/or silicon nitride, a reflector layer **3814**, which may comprise an aluminum layer, and a second insulating layer **3816**, which may comprise silicon nitride and/or silicon dioxide. By using a passivated reflector layer **3810**, light that impinges on the first face **182a** may be reflected back away from the carrier wafer **180**. In some embodiments, the first insulating layer **3812** may comprise silicon dioxide of thickness between about 2000 Å and 8000 Å; the reflector layer **3814** may comprise aluminum of thickness between about 100 Å and 5000 Å; and the second dielectric layer **3816** may comprise silicon nitride of thickness between about 2000 Å and 8000 Å. Other embodiments of a reflector **3810** may be provided. For example, a reflector may be embodied as a hybrid mirror, as is described, for example, relative to FIG. 54 below. In yet other embodiments, a reflector **3810** may be formed only of dielectric material having, for example, differing indices of refraction. For example, a distributed Bragg reflector may be used. In other embodiments, the reflector need not be used. Moreover, a passivated reflector **3810** may be used with any of the embodiments of FIGS. 17-36.

[0194] Still referring to FIG. 46, the LED wafer **3910** and the carrier wafer **180** are joined, so that the LED die anode and cathode contacts **160a** and **170a** are adjacent the first face **182a** of the carrier wafer **180** and the respective pairs of the LED die anode and cathode contacts **160a**, **160b** are electrically connected to the respective pairs of first contacts **1710a**, **1710b** on the first face **182a**.

[0195] Referring now to FIG. 47, shaping of the substrate **120** then takes place, for example by applying a saw blade **4720** across the substrate **120** at a uniform depth, to provide bevels **4710**. The bevels **4710** will have a different effect depending upon their location. In particular, between adjacent dies that are connected in series and/or in parallel, the bevels **4710a** will not reach the first trenches **4010**. Thus, the internal interconnection layer **145C** will remain intact between these adjacent LED dies that are connected in series and/or in parallel. However, between groups of LED dies that are to be connected in series and/or in parallel, the bevels **4710b** will penetrate into the second trenches **4510**, and thereby create an exposed surface that extends down to the active layer of the LED. Thus, the saw blade **4720** or



other shaping tool exposes the plurality of second trenches **4510**, but does not expose the plurality of first trenches **4010**.

**[0196]** It will also be understood that any other combination of substrate shaping techniques that were described herein, including texturing, the use of microlenses, the use of an additional x-cut and/or other shaping techniques may also be performed.

**[0197]** Referring now to FIG. **48**, wavelength conversion material **220** is then applied to the exposed surfaces of the LED wafer **3910** according to any of the techniques described herein. In some embodiments, the wavelength conversion material is applied using spraying. A single pass or multiple passes may be used, with each pass including the same or different compositions and/or concentrations of wavelength conversion material(s). As shown in FIG. **48**, the wavelength conversion material **220** is applied to the substrate **120** that was beveled, so that the wavelength conversion material **220** extends on a face of the substrate that is remote from the carrier wafer **180**, extends onto surfaces of the substrate **120** that were exposed by the beveling and also extends into the plurality of second trenches **4510** that were exposed. Accordingly, the sidewalls of the LED epi region **110** that are on the periphery of an LED chip may be covered by wavelength conversion material **120**, to reduce or prevent unwanted side emissions of, for example, blue light from taking place.

**[0198]** It will also be understood that protective layers and/or other layers or elements may be applied or placed according to any of the embodiments described herein, for example in FIGS. **1-36**.

**[0199]** Referring now to FIG. **49**, the carrier wafer **180** is singulated, for example using conventional singulation techniques, to produce a plurality of LED chips **4910**, a respective one of which includes a single carrier die **4920**, a respective single carrier die **4920** including a plurality of LED dies **4930** thereon that are electrically connected in series and/or in parallel.

**[0200]** It will be understood that various embodiments described herein in connection with FIGS. **17-36** may be combined with various embodiments described herein with respect to FIGS. **37-49**. For example, combinations of interconnections on the LED wafer and on the carrier wafer may be provided in some embodiments. Duplicate interconnections on the LED wafer and the carrier wafer may also be provided in some embodiments. Moreover, the interconnection in the LED wafer may be partly conductive and partly insulating, to provide crack reduction throughout the LED wafer, while also providing selective interconnection between adjacent LED dies, as desired. Finally, LED chips **4910** of FIG. **49** may then be further processed, such as by mounting on a light fixture mounting board and/or directly mounting in a light fixture, according to any of the embodiments described herein.

**[0201]** Additional discussion of various embodiments described herein will now be provided. In particular, the cross-sections of FIGS. **38-49** only illustrated a single anode contact **160** and a single cathode contact **170** for each LED die. However, in other embodiments, multiple anode contacts and/or multiple cathode contacts may be provided for a given LED die. For example, FIG. **50** illustrates a bottom view of an LED die **4930** of FIG. **49** that includes two anode contacts **160** that are of rectangular shape, and an array of twelve cathode contacts **170** that are circular in shape. Other numbers and shapes may be used in other embodiments. The

internal interconnection layer **145** electrically contacts the cathode contacts **170** and also extends beyond the LED die **4930** as shown. The internal interconnection layer **145** also electrically connects the anode contacts **160**, but does not electrically connect the anode contacts **160** to the cathode contacts **170**, which would short the LED die **4930**.

**[0202]** FIG. **51** illustrates four LED dies **4930** of FIG. **50** wired in series, as shown by the thick arrows **5110**. FIG. **51** illustrates how the patterned internal interconnection layer **145** can selectively electrically connect the anodes and cathodes of four LED dies **4930** in series.

**[0203]** FIG. **52** is a plan view of a carrier die **4920** for FIG. **49**, illustrating the thermal or neutral contact **2300**, and the through vias **196** for n- and p-contacts.

**[0204]** FIGS. **53A** and **53B** illustrate a series of 38 HRX, XQB and WLP LEDs mounted on a mounting board. Embodiments of FIGS. **53A** and **53B** may be configured, for example, as a replacement for a fluorescent tube.

**[0205]** In FIGS. **53A** and **53B**, the mounting boards are all of the same size of about 285 mm×15 mm, or about 4275 mm<sup>2</sup>. An individual HRX LED has an area of about 3 mm×3 mm, or about 9 mm<sup>2</sup> and may comprise a single die that is about 355 μm×711 μm in size. An individual XQB LED has an area of about 1.6 mm×1.6 mm, or about 2.56 mm<sup>2</sup> and may comprise two dies connected in parallel, where each die is about 35 μm×470 μm in size. Various embodiments of HRX LEDs are described, for example, in application Ser. No. 13/755,993 to Hussell et al, filed Jan. 31, 2013, entitled Submount Based Surface Mount Device (SMD) Light Emitter Components and Methods, the disclosure of which is hereby incorporated herein by reference in its entirety as if set forth fully herein. Moreover, various embodiments of XQB LEDs are described, for example, in U.S. patent application Ser. No. 13/649,052 to Lowes et al., filed Oct. 10, 2012, entitled LED Package With Encapsulant Having Planar Surfaces, the disclosure of which is hereby incorporated herein by reference in its entirety as if set forth fully herein. A WLP LED fabricated according to any of the embodiments described herein, may have an area of about 0.7 mm×0.7 mm, or about 0.49 mm<sup>2</sup>. As shown, each board includes 38 LEDs thereon. The individual LED area and the total LED area for 38 LEDs are shown in Table 1. The right hand column of Table 1 shows the percentage of the total board area taken up by the LEDs. As shown in Table 1, a remarkable decrease in the percentage of the board area taken up by the LEDs may be provided by WLP LEDs, according to various embodiments described herein.

TABLE 1

| LED  | LED Area             |                       | % LED to Board |
|------|----------------------|-----------------------|----------------|
|      | Individual           | Total                 |                |
| HRXS | 9 mm <sup>2</sup>    | 342 mm <sup>2</sup>   | 8%             |
| XQB  | 2.56 mm <sup>2</sup> | 97.28 mm <sup>2</sup> | 2%             |
| WLP  | 0.49 mm <sup>2</sup> | 18.62 mm <sup>2</sup> | 0.4%           |

**[0206]** Accordingly, Table 1 illustrates an LED chip according to various embodiments described herein that may be mounted on a board that has an area of at least 1,000 mm<sup>2</sup> in some embodiments, at least 2,500 mm<sup>2</sup> in other embodiments, at least 4,000 mm<sup>2</sup> in other embodiments, and about 4,275 mm<sup>2</sup> in still other embodiments, wherein at least 30 LEDs, and in some embodiments 38 LEDs, take up less than

1% of the board area in some embodiments, less than 0.5% of the board area in other embodiments, and about 0.4% of the board area in yet other embodiments, and can provide a replacement for a fluorescent tube in some embodiments.

[0207] It will be understood that various embodiments of FIGS. 1-36 may also be combined with various embodiments of FIGS. 37-53. For example, the various protective layers 222, 222', 222" that were illustrated in FIGS. 19, 20 and 30A-30C, may be incorporated into embodiments of FIGS. 37-53. Moreover, an individual dome 2510, as was illustrated in FIGS. 25 and 32, may also be incorporated into any of the embodiments of FIGS. 37-53. In addition, macro- and/or microlenses 2610, as were illustrated in FIGS. 26 and 31, may also be incorporated into any of the embodiments of FIGS. 37-53. Thus, various lenses in the form of a cube, a dome, an overmold and/or a microlens may be provided in any of the embodiments described herein. Finally, any of the internal structures or manufacturing techniques of FIGS. 1-36 may be incorporated into embodiments of FIGS. 37-53 and vice versa. For example, the internal structure of an LED die, the internal interconnection structures, the substrate shaping, singulation, wavelength conversion layer configuration of FIGS. 37-53 may be incorporated into any of FIGS. 1-36, and LED fabrication, chip fabrication and module/fixture fabrication of FIGS. 1-36 may also be incorporated into embodiments of FIGS. 37-53. Finally, although FIGS. 1A-1U, 6, 9A-9B, 17-27 and 35 illustrated individual LED dies, these LED dies may be provided in a common substrate, as was illustrated in FIGS. 38-52 herein. Stated differently, there may be no need to singulate individual LED dies in embodiments of FIGS. 1-36, but, rather, a common substrate may be retained, as was illustrated in FIGS. 37-53.

[0208] The remaining portion of this DETAILED DESCRIPTION includes the detailed description of FIGS. 1-13C of application Ser. No. 13/790,369, except that the figures have been renumbered as FIGS. 54-66C herein.

[0209] FIG. 54 is a cross-sectional view of a light emitting diode structure 100A according to various embodiments. Referring to FIG. 54, these light emitting diodes include a diode region 110 having first and second opposing faces 110a, 110b, respectively, and including therein an n-type layer 112 and a p-type layer 114. Other layers or regions 116 may be provided which may include quantum wells, buffer layers, etc., that need not be described herein. The diode region 110 also may be referred to herein as an "LED epi region", because it is typically formed epitaxially on a substrate 120. For example, a Group III-nitride based LED epi region 110 may be formed on a silicon carbide growth substrate 120. In some embodiments, as will be described below, the growth substrate 120 may be present in the finished product. In other embodiments, the growth substrate 120 may be removed.

[0210] Continuing with the description of FIG. 54, an anode contact 125, also referred to as a "p-contact", ohmically contacts the p-type layer 114 and extends on the first face 110a of the diode region 110. The anode contact 125 may extend to a greater or less extent on the p-type layer 114 than illustrated in FIG. 54. An insulating layer 140 also extends on the first face 110a outside the anode contact 125. The insulating layer 140 may include a transparent material, such as SiN and/or SiO<sub>2</sub>. The insulating layer may also include a multilayer structure, such as a multi-layered stack of insulating materials. A reflective cathode contact 150, also

referred to as an "n-contact" electrically contacts the n-type layer 112 and extends through the insulating layer 140 and onto the insulating layer 140 that is outside the anode contact 125. In some embodiments, the reflective cathode contact 150 may directly and ohmically contact the n-type layer 112. In other embodiments, however, a thin ohmic contact layer (not shown), such as a layer of titanium, may provide the actual ohmic contact to the n-type layer 112. The insulating layer 140 and the reflective cathode contact 150 can provide a hybrid reflective structure or "hybrid mirror", wherein the underlying insulating layer 140 provides an index refraction mismatch or index step to enhance the total internal reflection (TIR) from the reflective layer 150 compared to absence of the underlying insulating layer 140. It will also be understood that, in other embodiments, the insulating layer 140 may comprise multiple sublayers, such as oxide and nitride sublayers to provide, for example, a distributed Bragg reflector. Moreover, the reflective cathode contact 150 may also include a plurality of sublayers.

[0211] As also shown in FIG. 54, in some embodiments, a via 118 extends into the first face 110a to expose the n-type layer 112, and the insulating layer 140 extends into the via 118. Moreover, the reflective cathode contact 150 also extends on the insulating layer 140 into the via 118, to electrically, and in some embodiments ohmically, contact the n-type layer 112 that is exposed in the via 118.

[0212] An anode bond pad 160 is also provided that is electrically connected to the anode contact 125. A cathode bond pad 170 is also provided that is electrically connected to the reflective cathode contact 150. As shown, the anode and contact pads 160 and 170 extend on the first face 110a in closely spaced apart relation to one another, to define a gap 172 therebetween. The gap may be filled with an insulator as described below. In any embodiments illustrated herein, the gap 172 may occur at any desired position and is not limited to the position illustrated herein. In some embodiments, the cathode bond pad 170 may be made as large as possible, so that it can be directly coupled to a grounded heat sink for enhanced thermal dissipation in a flip-chip mounting configuration, without the need for an intervening electrically insulating layer that could reduce thermal efficiency.

[0213] As also shown in FIG. 54, a transparent substrate, such as a transparent silicon carbide growth substrate 120, may be included on the second face 110b of the diode region 110. The transparent substrate 120 may include beveled sidewalls 120a and may also include an outer face 120b that is remote from the diode region 110. As shown, the outer face 120b may be textured. The thickness of the substrate 120, the resistivity of the substrate, geometry of the sidewalls 120a and/or the texturing of the remote face 120b may be configured to enhance the far field emission of radiation from the diode region 110 through the substrate 120. The emission from the diode region 110 may take place directly from the diode region 110 through the substrate 120 and may also take place by reflection from the reflective cathode contact 150 back through the diode region 110 and through the substrate 120. In some embodiments, reflection may also take place from the anode contact 125, as will be described in detail below.

[0214] As also shown in FIG. 54, in some embodiments, when the transparent substrate 120 is sapphire, Patterned Sapphire Substrate (PSS) technology may be used to texture the interface between the sapphire substrate 120 and the

diode region **110**, as shown by the jagged interface between the substrate **120** and the second face **110b** of the diode region **110**. As is well known, PSS technology may provide texture features that may be, for example, about 3  $\mu\text{m}$  in size on an about 5  $\mu\text{m}$  pitch (feature to feature distance). Other sizes/pitches and/or random sizes/pitches may also be used. The use of PSS technology can enhance the extraction efficiency between the gallium nitride-based diode region **110** and the index mismatched sapphire substrate **120**.

**[0215]** Accordingly, some embodiments of the invention can provide an LED that is suitable for flip-chip mounting (i.e., mounting opposite the orientation of FIG. **54**), wherein the anode bond pad **160** and the cathode bond pad **170** are mounted on a supporting substrate, such as a printed circuit board or other wiring board, and emission of light takes place through the substrate **120** remote from the anode bond pad **160** and the cathode bond pad **170**. Thus, a lateral LED may be provided wherein both the anode contact **125** and the cathode contact **150** extend on a given face of the diode region (i.e., the first face **110a**), and emission takes place remote from the anode and cathode contacts **125** and **150**, respectively, through the second face **110b** of the diode region, and through the substrate **120**. In other embodiments, the substrate may be removed so that emission takes place directly from the second face **110b** of the diode region **110**.

**[0216]** As was noted above, the geometry of the substrate **120** may be configured to provide a desired far field emission pattern, such as Lambertian emission. Moreover, texturing may take place on the sidewalls **120a** and/or on the face **120b** of the substrate **120**. Many different configurations of texturing may be used including random texturing, microlenses, microarrays, scattering regions and/or other optical regions. According to some embodiments, the outer face **120b** may be differently textured in a first portion **120c** thereof than a second portion **120d** thereof, so as to provide an orientation indicator for the light emitting diode. Thus, as shown in FIG. **54**, an array of microlenses **120d** may be provided except at a given area adjacent the transparent cathode contact, wherein a small bar **120c** or other indicator, such as a “+” sign, may be provided. The different texturing on the remote face **120b** of the substrate can provide an orientation indicator that can allow pick-and-place equipment to correctly orient the LED for packaging, even if the structure of the LED is not “visible” to the pick-and-place equipment through the textured substrate.

**[0217]** In some embodiments, the anode contact and/or the cathode contact can provide a reflective structure on the first face **110a** that is configured to reflect substantially all light that emerges from the first face **110a** back into the first face **110a**. The reflective structure further includes the insulating layer **140** beneath the cathode contact **150** and extensions thereof **150a**. In particular, in some embodiments, the reflective structure reflects the light that emerges from at least 90% of an area of the first face **110a**. The reflective structure may comprise reflective materials that themselves reflect at least 90% of the light that impinges thereon. In some embodiments, the anode contact **125** may be a reflective anode contact that ohmically contacts the p-type layer **114**. In these embodiments, the reflective structure may be provided by a reflective surface of the anode contact **125** that ohmically contacts the p-type layer **114**, a reflective surface of the cathode contact **150** that ohmically contacts the n-type layer **112** and a reflective surface of extensions of the

cathode contact, identified as **150a** in FIG. **54**, that extend onto the first face **110a** between the via **118** and the anode contact **125**, in combination with the insulating layer **140**. In other embodiments, the anode contact **125**, may be transparent, and the reflective cathode contact **150**, specifically the extensions **150a** of the reflective cathode contact **150**, may extend onto the transparent anode contact **125** to provide a reflective structure in combination with the insulating layer **140**. Thus, in some embodiments, the reflective cathode contact can extend to cover substantially all of the first face that is outside the anode contact with the reflective cathode contact. In other embodiments, the reflective cathode contact can cover substantially all of the first face that is outside the anode contact with the reflective cathode contact, and also can cover at least a portion of the anode contact with the reflective cathode contact. More detailed embodiments will be described below.

**[0218]** Accordingly, some embodiments may provide LEDs with a lateral flip-chip configuration. Some embodiments may provide dual mirrors on the p-type and n-type layers. Moreover, the n-type mirror may be an integrated n-contact mirror that can make electrical contact with at least one n-type layer of the LED epi, and can also extend over at least one p-type contact of the LED epi. The integrated n-contact mirror may include a material, such as aluminum, that is optically reflective to wavelengths generated by the LED epi. The transparent insulating layer and the reflective layer can provide a hybrid reflective structure or “hybrid mirror”, wherein the underlying transparent insulating layer provides an index of refraction mismatch or index step to enhance the TIR from the diode region compared to absence of the underlying transparent insulating layer. Moreover, the light emitting face of the LED chip, opposite the mirror(s), may include a growth substrate. The growth substrate may further include a shaped surface, such as tapered sidewalls and/or texturing, for light extraction purposes. The amount of tapering and/or texturing may be related to the total thickness of the LED, including the growth substrate. The geometry of the substrate (e.g., thickness/sidewall bevels) and/or the texturing thereof may be adjusted to achieve desired far-field emission patterns. Moreover, since the substrate need not conduct current, it can have high resistivity so that it can be transparent.

**[0219]** LED chips according to various embodiments may be more rugged or robust than conventional LED chips. In particular, the only exposed surfaces of the LED chip may be solid p- or n-contact portions on one side, and the growth substrate on the other side. In contrast, conventional LED chips may need fragile wire bonds and may include exposed top and/or bottom portions of the LED epi.

**[0220]** Moreover, it has also been found, according to various embodiments, that the provision of a transparent insulating layer between the diode region and the reflective cathode contact may actually enhance the reflectivity from the diode region by providing an index mismatch or index step. Accordingly, as shown, for example, in FIG. **54**, the insulating layer **140** can provide an integral optical element for the reflective cathode contact **150**, in addition to providing desired electrical insulation for the LED. Moreover, the insulating layer **140** and the reflective cathode contact **150** can provide a hybrid mirror.

**[0221]** An explanation of the operation of the insulating layer **140** as part of a hybrid reflector will now be provided. In particular, LEDs typically include multiple layers of

different materials. As a result, light emitted from the active region must typically pass through or across one or more of such layers before exiting the LED. Snell's law dictates that the photons will be refracted as they pass from one material to the next. The angles at which the photons will be refracted will depend upon the difference between the refractive indexes of the two materials and the angle of incidence at which the light strikes the interface.

[0222] In an LED, although some reflected light will still escape the LED at some other location, a certain percentage will be totally internally reflected, never escape the LED, and will thus functionally reduce the external efficiency of the LED. Although the individual reduction in the percentage of photons escaping may appear to be relatively small, the cumulative effect can be significant, and LEDs that are otherwise very similar can have distinctly different performance efficiencies resulting from even these small percentage losses.

[0223] Snell's law dictates that when light crosses an interface into a medium with a higher refractive index, the light bends towards the normal. Similarly, when light travels across an interface from a medium with a high refractive index to a medium with a lower refractive index, light bends away from the normal. At an angle defined as the critical angle, light traveling from a medium with a high refractive index to a medium with a lower refractive index will be refracted at an angle of 90°; i.e., parallel to the boundary. At any angle greater than the critical angle, an incident ray undergoes total internal reflection (TIR). The critical angle is thus a function of the ratio of the refractive indexes. If the light hits the interface at any angle larger than this critical angle, the light will not pass through to the second medium at all. Instead, the interface reflects the light back into the first medium, a process known as total internal reflection. The loss of light due to this total internal reflection is known as the critical angle loss, and is another factor that reduces the external efficiency of the LED.

[0224] Embodiments of a hybrid mirror described herein use index mismatching to enhance total internal reflection (TIR) based on Snell's law. In order to enhance TIR, it is desired to provide a large index change to a lower refractive index material relative to the GaN-based diode region. Thus, any light outside the escape cone angle given by Snell's law is internally reflected back into the diode region, and can have essentially no loss. The reflective cathode contact 150 and/or a reflective anode contact can then be used to reflect the fraction of the light impinging thereon from an omnidirectional light source. Accordingly, both the transparent insulating layer 140 and the reflective cathode contact act as a hybrid reflector according to various embodiments to enhance reflection of light emerging from the diode region back into the diode region.

[0225] Other embodiments of the invention can provide a reflective layer for a vertical LED. Thus, light emitting diodes according to various embodiments may also comprise a diode region including therein an n-type layer and a p-type layer, and a contact for one of the n-type layer or the p-type layer. The contact may comprise an insulating layer 140 on the one of the n-type layer or the p-type layer that has an index of refraction that is less than the one of the n-type layer or the p-type layer. A reflective layer 150 is provided that electrically contacts the one of the n-type layer or the p-type layer, and that extends on the transparent insulating layer. Accordingly, the insulating layer 140 can provide an

integral optical element for a reflective layer 150 so as to provide a hybrid mirror that can improve the reflectivity of the reflective layer 150 compared to absence of the insulating layer 140, because the transparent insulating layer provides an index mismatch or index step to the diode region 110. In other embodiments, the reflective layer 150 can also electrically contact, and in some embodiments ohmically contact, the one of the n-type layer or the p-type layer, and may extend through the insulating layer 140 to make this contact. In still other embodiments, a second contact may be provided for the other of the n-type layer or the p-type layer. The second contact may comprise a second reflective layer that ohmically contacts the other of the n-type layer or the p-type layer. In other embodiments, the second contact may comprise a transparent conductive layer that ohmically contacts the other of the n-type layer or the p-type layer, and the insulating layer 140 and the reflective layer 150 can both extend onto the transparent conductive layer.

[0226] Moreover, various embodiments as described herein can also provide a diode region 110 having first and second opposing faces 110a, 110b, and including therein an n-type layer 112 and a p-type layer 114. A reflective anode contact 125 ohmically contacts the p-type layer and extends on the first face 110a. A reflective cathode contact 150 ohmically contacts the n-type layer and extends on the first face. The reflective anode contact 125 and the reflective cathode contact 150 are configured to reflect substantially all light that emerges from the first face 110a back into the first face 110a. Stated differently, the reflective cathode contact 150 can cover substantially all of the first face 110a that is outside the anode contact 125. Moreover, in other embodiments, the reflective cathode contact 150 can also cover at least a portion of the anode contact 125.

[0227] FIG. 55 is a cross-sectional view of an LED structure 100B according to other embodiments. In these embodiments, a reflective anode contact is provided in addition to a reflective cathode contact.

[0228] More specifically, in FIG. 55 a diode region 110 is provided as was described in connection with FIG. 1. A substrate 120 is also provided, although it need not be provided in other embodiments. The substrate 120 may be thinned relative to the thickness of the growth substrate. A reflective anode contact 130 is provided that ohmically contacts the p-type layer 114 and extends on the first face 110a. The reflective anode contact may include silver. In some embodiments, the reflective anode contact 130 may include a two-layer structure including, for example, about 5 Å of nickel (Ni) directly on the p-type layer 114 and about 1000 Å of silver (Ag) on the nickel, to thereby provide an "NiAg mirror" 130. The reflective anode contact 130 can reflect at least 90% of the visible light from the diode region 110 that impinges thereon. Other reflective layers that also provide an ohmic contact to p-type gallium nitride may be used in other embodiments. It will be understood that the reflectivity of the NiAg mirror is determined primarily by the Ag because only a very thin layer (in some embodiments less than about 10 Å) of Ni is used. Moreover, when annealed, this nickel may convert to nickel oxide to enhance the ohmic contact for the Ag to the p-type gallium nitride. Thus, the NiAg mirror 130 can have about the same reflectivity of Ag alone, but can provide a better contact and lower voltage to the p-type layer. In other embodiments, pure Ag may be used.

[0229] Surmounting the NiAg mirror **130** is a barrier layer **132** which may include sublayers comprising about 1000 Å of titanium tungsten (TiW), about 500 Å of platinum (Pt) and about 1000 Å of titanium tungsten (TiW). The titanium tungsten/platinum sublayers may repeat in multiple repetitions to provide a desired diffusion barrier. The diffusion barrier layer **132** generally is not reflective. Thus, the face of the NiAg mirror **130** that is directly on the p-type layer **114** provides a reflective structure.

[0230] Continuing with the description of FIG. **55**, an insulating layer **140** is provided on the sidewalls of the via **118** and on the first face **110a** outside the via **118**. In some embodiments, as shown, the insulating layer **140** may also extend onto at least a portion of the NiAg mirror **130**. In some embodiments, the insulating layer **140** may comprise about 1 μm of silicon nitride (SiN) and/or about 0.5 μm of silicon dioxide (SiO<sub>2</sub>). The thickness of the transparent insulating layer may be configured to enhance the reflectivity from the reflective cathode contact **150**, based on the operating wavelength of the LED and/or the index of refraction of the insulating layer, using techniques known to those skilled in the art. In particular, silicon dioxide may have an index of refraction of about 1.5 while SiN may have an index of refraction of about 2.0, both of which are less than the index of refraction of gallium nitride (about 2.5), so that an index mismatch or index step is provided by the insulating layer **140**, which can actually enhance TIR from the diode region **110**.

[0231] As also shown in FIG. **55**, the reflective cathode contact **150** can ohmically contact the n-type layer **112**, for example on the floor of the via **118** and can extend on the insulating layer **140** on the sidewall of the via **118**, and may also extend onto the insulating layer **140** that is outside the via **118** as indicated by **150a**. In some embodiments, the reflective cathode contact **150** may comprise about 1500 Å of aluminum. Thicker reflective cathode contacts also may be used. The hybrid reflector that includes the insulating layer **140** and the aluminum reflective cathode contact **150** can reflect at least 90% of the visible light from the diode region **110** that impinges thereon. In other embodiments, a separate ohmic contact layer **250** may be provided between the reflective cathode contact **150** and the n-type layer **112**, to provide an ohmic contact to the n-type layer **112**. In some embodiments, the ohmic contact layer **250** may comprise titanium, for example annealed titanium, or aluminum/titanium alloy. It will be understood that the ohmic contact layer **250** may be used in any and all of the embodiments described herein between the reflective contact **150** and the n-type or p-type layer.

[0232] Finally, an anode bond pad **160** and a cathode bond pad **170** are provided. The anode bond pad **160** and the cathode bond pad **170** can include a stack of about 500 Å titanium (Ti), about 2000 Å nickel (Ni) and about 1-3 μm of 80/20 gold-tin (AuSn) alloy, to provide "TiNiAuSn pads". Other materials may be used, and not all of these layers may be used. For example, pure tin may be used as it has a lower melting point. Moreover, in other embodiments, a plating seed layer may be provided on the anode contact and on the reflective cathode contact, and at least a portion of the anode and/or cathode bond pads are plated on the seed layer. In still other embodiments, the reflective cathode contact **150** and/or the barrier layer **140** may provide the plating seed layer

for plating the pads **160/170** thereon. The plated anode and cathode bond pads can also provide mechanical support and enhanced thermal efficiency.

[0233] Accordingly, embodiments of FIG. **55** may provide a reflective structure on the first face **110a** that is configured to reflect substantially all light, for example, at least 90% of the light that emerges from the first face **110a** back into the first face **110a**. In embodiments of FIG. **55**, the reflective structure comprises two different reflectors. More specifically, the reflective structure comprises a reflective surface of the anode contact **130** that ohmically contacts the p-type layer **114**, a reflective surface of the cathode contact **150** that ohmically contacts the n-type layer **112** and a reflective surface of extensions **150a** of the cathode contact **150** that extend between the reflective surface of the anode contact **130** that ohmically contacts the p-type layer **114** and the hybrid reflective surface of the cathode contact **150** in combination with the insulating layer **140**. When viewed from the perspective of the diode region **110**, substantially all the light that emerges from the diode region **110** into the anode and cathode contacts can be reflected back into the diode region. Thus, from an area standpoint, the reflective structure of FIG. **55** can reflect the light that emerges from at least 85% of the area of the first face, and in some embodiments, at least 90% of the area. In other words, at least 90% of the diode face can be covered by mirror. Moreover, since the reflective structure can comprise nickel-silver (anode contact **130**) and aluminum (cathode contact **150**), at least 90% of the light that impinges on the reflective structure may be reflected. In other words, the mirror may have at least 90% efficiency.

[0234] Other LED structures, such as the structures illustrated in U.S. Patent Publication No. 2009/0283787, the disclosure of which is incorporated herein by reference and which is assigned to the assignee of the present invention, included a barrier layer that surrounded the p-type ohmic contact and contacted the underlying p-type layer. Such a barrier layer formed a non-ohmic contact to the p-type layer and was optically absorbing, which caused some loss of light in the chip. Embodiments of the present invention protect the edges of the anode contact **130** with an insulating structure that forms a hybrid reflector with the cathode contact **150**, which may increase the amount of light exiting the chip. As the barrier layer **130** is contained within the periphery of the reflective anode contact **130**, it may not absorb light generated in the active region **116** of the LED chip, as it is hidden from the active region by the reflective anode contact **130**.

[0235] When an LED chip structure as illustrated in FIG. **54** or **55** is flip-chip mounted onto a submount or other surface, mechanical force may be applied to the LED chip in a thermosonic or thermocompressive bonding process. In some bonding processes, such as a flux eutectic AuSn reflow attach process at 320° C., no external force may be applied to the chip. However, stress can be imparted to the LED chip due to mismatches in the coefficients of thermal expansion of various materials in the chip structure and the package substrate layers when the chip is bonded at high temperature. Even if a lower temperature mounting process is used, it may be desirable for an LED chip structure to be able to tolerate subsequent reflow temperatures of at least about, for example, 260° C. which may occur when the completed component is mounted onto a printed circuit board or other support substrate.

[0236] Many different bonding processes can impart mechanical stress to the LED chip, and in particular can impart mechanical stress to the insulating layer 140, potentially resulting in the formation of hairline cracks 135 in the insulating layer 140. In most locations, these hairline cracks 135 may not adversely affect the operation or reliability of the LED chip. However, if a hairline crack 135 occurs at a location where it extends from the anode contact 132 to an external surface of the chip, or to the cathode contact 150, then silver or other metal in the anode contact 130 can migrate through the hairline crack. This migration of metal can cause an electrical short to form between the anode contact 130 and the cathode contact 150, which can render the LED chip inoperable.

[0237] FIG. 56 is a detailed close-up view of a portion of the LED chip 100B shown in FIG. 55. As shown in FIG. 56, if a hairline crack 135 forms that extends from the anode contact 132 to an exterior surface 106 of the LED chip, silver or other metal in the anode contact 130 may migrate through the crack 135, and flow onto the outside of the chip. An unwanted external metal flow 137 may contact the n-type layer 112, which can also result in an undesirable electrical short circuit.

[0238] Silver migration may be exacerbated by the presence of moisture. Thus, for example, cracks occurring in the insulating layer 140 near an outer surface or edge surface of the LED chip structure may be more susceptible to the formation of electric short circuits due to silver migration.

[0239] Some embodiments of the present inventive concepts may mitigate the effect of cracks in the insulating layer 140 so that such cracks may not propagate entirely through the insulating layer 140, and/or may not provide a migration path in an area that is likely to result in an electrical short-circuit.

[0240] FIGS. 57A to 61B illustrate methods of forming an LED structure 100C including a crack-tolerant transparent insulating layer in accordance with some embodiments. In particular, FIGS. 57A, 58A, 59A, 60A, and 61A are plan views of intermediate LED device structures, and FIGS. 57B, 58B, 59B-59F, 60B and 61B are cross-sections of the intermediate LED device structures shown in FIGS. 57A, 58A, 59A, 60A, and 61A, respectively.

[0241] Referring to FIGS. 57A and 57B, a preliminary LED device structure includes an optional substrate 120, one or more n-type layers 112, an active region 116, and one or more p-type layers 114. The structure and composition of these layers is described in detail above and will not be repeated for brevity. The substrate 120 may include light extraction features as illustrated above in connection with FIG. 54. However, such features are omitted from the following figures for clarity.

[0242] For convenience, the active region 116 will be omitted from subsequent figures. However, it is understood that an active region will generally be present between the n-type layers 112 and the p-type layers 114.

[0243] Referring still to FIGS. 57A and 57B, a layer 130 of a reflective material, such as silver or nickel silver, is deposited on the upper surface of the p-type layers 114 as a reflective anode contact. The reflective layer 130 is patterned to form an aperture 138 in which the via 118 will be formed.

[0244] Referring to FIGS. 58A and 58B, a barrier layer 132 of, for example, titanium tungsten, tungsten, platinum or other suitable material is deposited on the reflective anode contact 130 and patterned to expose the aperture 138. The

outer edges of the barrier layer 132 may be slightly recessed back from the peripheral edges of the reflective anode contact 130.

[0245] Referring to FIGS. 59A and 59B, a via 119 may be etched through the p-type layers 114 and the active region 116 (not shown) down to the n-type layers 112. A separate mask may be used or the reflective anode contact 130 and/or barrier layer 132 may be used as an etch mask to form the via 119.

[0246] Referring to FIG. 59C, a base insulating layer 140A may be blanket-deposited over the structure to cover the exposed portions of the transparent anode contact 130 and the barrier layer 132. The insulating layer 140A may extend into the via 119 and onto exposed portions of the p-type layers 114, the active layers 116 (not shown) and the n-type layers 112. The base insulating layer 140A may include a dielectric material, such as SiN, SiO<sub>2</sub>, etc., and may have a thickness of between about 250 nm and 1 micron, and in particular embodiments may have a thickness of about 500 nm.

[0247] Referring to FIG. 59D, a crack reducing interlayer 145 is deposited over the base insulating layer 140A. In particular, the crack reducing interlayer 145 may include a material that is capable of reducing the propagation of cracks through the insulating layer. Thus, the crack reducing interlayer 145 may in some embodiments have a composition different than the insulating layer. While not wishing to be bound by a particular theory, it is presently believed that the crack reducing layer may stop cracks from propagating through the insulating layer when the crack reducing layer has a different fracture mode compared to the insulating layer. For example, silicon dioxide is characterized by having a brittle fracture mode, while metals typically have a ductile fracture mode. When a material has a ductile fracture mode, it undergoes plastic deformation before fracturing, while a material with a brittle fracture mode may not exhibit plastic deformation before fracturing. Providing a material with a ductile fracture mode as an interlayer within an insulating material having a brittle fracture mode may result in reduction of crack propagation, because the stress that causes cracks to propagate through the (brittle) insulating layer may not cause enough plastic deformation in the (ductile) interlayer to allow it to crack. Moreover, the cracks may themselves may provide some amount of strain relief to the insulating layer, which may reduce the amount of strain applied to the interlayer.

[0248] The crack reducing layer may also form an interface with the insulating layer that relieves stress in the structure when the crack propagates to the interface. That is, for example, slippage at the interface between the insulating layer and the crack reducing layer may result in stress relief at the interface, which may stop the propagation of cracks.

[0249] In some embodiments, the crack reducing interlayer 145 may include a material other than a dielectric material. In some embodiment, the crack reducing interlayer 145 may include a non-crystalline material, such as an amorphous material. The crack reducing interlayer 145 may include, for example, a metal such as aluminum (Al), titanium (Ti), tungsten (W), AlTi, AlTiW, TiW, or other metal. In some embodiments, the crack reducing interlayer 145 may include a polymer material, such as benzocyclobutene (BCB), polyimide, etc. In some embodiments, the polymer material may be a ductile polymer.

[0250] In order to withstand subsequent processing steps, the polymer may be a high temperature polymer, and in some embodiments may be able to tolerate temperatures up to about 300° C. or more.

[0251] The crack reducing interlayer 145 may have a thickness of about 10 nm to 1 micron. When the crack reducing interlayer 145 includes Al, the crack reducing interlayer 145 may have a thickness of about 150 nm.

[0252] In some embodiments, the crack reducing interlayer 145 may be fabricated to be thin enough as to be optically transparent. In other embodiments, the crack reducing interlayer 145 may be optically absorbing. For example, since the layer 130 may be reflective, light generated in the device may be reflected away from the crack reducing interlayer 145 and not absorbed thereby. In some embodiments, the crack reducing interlayer 145 may itself be reflective, such as when the crack reducing interlayer 145 comprises aluminum.

[0253] Referring to FIG. 59E, the crack reducing interlayer 145 may be patterned using, for example, photolithography, to form a gap or moat 146 that separates the crack reducing interlayer 145 into two separate portions 145A and 145B as shown in FIG. 60A and discussed in more detail below. The crack reducing interlayer 145 may also be patterned to form an aperture 147 therein that will be used to define a contact location for the anode contact of the device, as discussed in more detail below.

[0254] Referring to FIG. 59F, an upper insulating layer 140B may be blanket deposited over the structure. The upper insulating layer 140B may have the same composition or a different composition as the lower insulating layer 140A. The upper insulating layer 140B may include a dielectric material, such as SiN and/or SiO<sub>2</sub>, and may have a thickness of about 250 nm to about 1 micron. In particular embodiments, the upper insulating layer 140B may include SiN, and may have a thickness of about 500 nm. In some embodiments, the thickness of the upper and lower insulating layers 140A, 140B may be selected based on the level of voltage that such layers may be required to withstand for electrostatic discharge protection. For example, if a portion of the crack reducing interlayer 145 is electrically connected to the cathode contact, the base insulating layer 140A may be required to withstand a voltage of at least about 50 V.

[0255] Referring to FIGS. 60A and 60B, the insulating layer 140 including the base insulating layer 140A, the crack reducing interlayer 145 and the upper insulating layer 140B may be patterned to open first and second vias 131 and 118 therein. The first via 131 extends through the insulating layer 140 to the barrier layer 132, while the second via 118 extends through the insulating layer 140 to the n-type layers 112. As shown in FIG. 60B, the crack reducing interlayer 145 may be spaced apart from the vias 131, 118 so that sidewalls of the crack reducing interlayer 145 are not exposed by the vias 131, 118. However, in other embodiments, one or both of the vias 131, 118 may expose portions of the crack reducing interlayer 145, as illustrated in FIG. 62, and discussed in more detail below.

[0256] The gap or moat 146 that separates the crack reducing interlayer 145 into two separate portions 145A and 145B is illustrated in FIG. 60A.

[0257] Referring to FIGS. 61A and 61B, a reflective cathode contact 150 is formed within the second via 118, and may extend onto the insulating layer 140 over the p-type layers and over the crack reducing interlayer 145. A cathode

bond pad 170 is formed on the reflective cathode contact 150, and an anode bond pad 160 is formed in the first via 131 to contact the barrier layer 132. Additional layers, such as adhesive or bonding layers may also be included. The outside edges of the anode bond pad 160 may be formed within the periphery of the first crack reducing interlayer portion 145A, and the outside edges of the reflective cathode contact 150 and the cathode bond pad 170 may be formed within the periphery of the second crack reducing interlayer portion 145B as best seen, for example, in the plan view of FIG. 61A.

[0258] The presence of the crack reducing interlayer 145 within the insulating layer 140 may prevent or reduce cracks that form in the insulating layer 140 from penetrating completely through the insulating layer 140 so as to form migration paths for metal in the device. That is, although cracks can still form in the insulating layer 140, such cracks may not lead to the formation of electrical short circuits that can damage the device. While not wishing to be bound by any particular theory, it is presently believed that the interface between the crack reducing interlayer 145 and the insulating layer 140 provides a mechanical discontinuity that can reduce the propagation of cracks through the insulating layer 140. Accordingly, any material that provides a suitable mechanical discontinuity with the insulating layer 140 may be suitable for use as the crack reducing interlayer 145, regardless of whether such material is electrically conductive or electrically insulating. The material of the crack reducing interlayer 145 may be transparent, reflective, or opaque.

[0259] In the mounting process, mechanical stress may be placed on the LED chip through the anode bond pad 160 and/or the cathode bond pad 170. Thus, cracks in the insulating layer 140 may tend to originate underneath these pads. Accordingly, a device according to some embodiments may be designed such that the anode bond pad 160 and the cathode bond pad 170 are formed within the periphery of the respective portions 145A, 145B of the crack reducing interlayer 145, so that any cracks that form in the upper portion 140B of the transparent insulating layer underneath the pads may be less likely to propagate through the insulating layer 140 to the barrier layer 132 or the reflective anode contact 130.

[0260] The respective portions 145A, 145B of the crack reducing interlayer 145 may be electrically isolated from one another by the gap 146 (FIG. 60B) to reduce the possibility of a short circuit.

[0261] FIG. 62 is a cross sectional view of an LED chip structure 100D in accordance with further embodiments. As shown therein, the portion 145A of the crack reducing interlayer 145 may contact the anode bond pad 160, while the portion 145B of the crack reducing interlayer 145 may contact the cathode bond pad 160 and/or the reflective cathode contact 150. Thus, in embodiments where the crack reducing interlayer 145 includes a conductive material such as aluminum, one or both of the portions 145A, 145B of the crack reducing interlayer 145 may be electrically active. However, as the portions 145A, 145B of the crack reducing interlayer 145 are isolated from one another by the gap or moat 146, such contact may not cause a short circuit.

[0262] FIG. 63A is a cross sectional view of an LED chip structure 100E in accordance with further embodiments. In the embodiment shown in FIG. 63A, the crack reducing interlayer 145 does not include a gap. However, the crack

reducing interlayer 145 is spaced apart from the anode and cathode contacts by portions of the insulating layer 140 so that it is electrically isolated (floating).

[0263] FIG. 63B is a cross sectional view of an LED chip structure 100E' in accordance with further embodiments. In the embodiment shown in FIG. 63B, the crack reducing interlayer 145 does not include a gap and is not spaced apart from the anode and cathode contacts of the device by portions of the insulating layer 140. In the embodiments of FIG. 63B, the crack reducing interlayer 145 may be an electrically insulating material, such as BCB, and the insulating layer 140 may thereby have structure including three distinct layers 140A, 145 and 140B.

[0264] FIG. 64 is a cross sectional view of an LED chip structure 100F in accordance with further embodiments. In the embodiment shown in FIG. 64, a crack reducing layer 155 is on the insulating layer 140 between the insulating layer 140 and the bond pads 160, 170. In the embodiments illustrated in FIG. 64, the crack reducing layer 155 may be formed of an electrically insulating material, such as a polymer.

[0265] FIGS. 65A and 65B are a plan view and a cross sectional view, respectively, of an LED device structure 100G that has a crack-tolerant transparent insulating layer according to further embodiments. The LED structure shown in FIGS. 65A and 65B includes an optional substrate 120, n-type layers 112, p-type layers 114, a reflective anode contact 130, a barrier layer 132, an insulating layer 140, an anode bond pad 160 and a cathode bond pad 170.

[0266] In the LED structure shown in FIGS. 65A and 65B, the portion 140A of the insulating layer 140 near the peripheral edges of the chip are mechanically isolated from the portions of the insulating layer 140 underneath the anode bond pad 160 and the cathode bond pad 170 by a trench 175 that extends around the anode bond pad 160 and the cathode bond pad 170. The trench 175 extends through the insulating layer 140 to the barrier layer 132.

[0267] Peripheral portions 140A of the insulating layer 140 remain on and protect the external edges of the reflective anode contact 130. However, any cracks that may develop underneath the anode bond pad 160 and/or cathode bond pad 170 may not propagate to the external edges of the reflective anode contact that are most susceptible to moisture-assisted metal migration. Accordingly, cracks that form in the insulating layer 140 underneath the anode bond pad 160 and/or cathode bond pad 170 may not result in undesirable short circuits due to metal migration.

[0268] An optional second passivation layer including about 150 nm of SiN may be deposited on the structure to cover the portions of the barrier layer 132 exposed by the trench 175.

[0269] FIG. 65C is a cross sectional view of a device structure 100G' in accordance with further embodiments. The device structure 100G' is similar to the device structure 100G shown in FIG. 65B, except that the trench 175' does not extend completely through the insulating layer 140 to contact the barrier layer 132. Even though the trench 175' does not extend completely through the insulating layer 140, the trench 175' may still be effective to block a significant number of cracks from propagating to the edge of the structure and causing failures, while still providing protection to the entire upper surface of the barrier layer 132. Thus, the trench 175' may not need to provide physical complete separation of the insulating layer 140 to be effective.

[0270] Reference is now made to FIGS. 66A and 66B, which are a plan view and a cross sectional view respectively of an LED device structure 100H that has a crack-tolerant insulating layer according to still further embodiments. The LED structure 100H includes both a trench 175 for mechanically isolating peripheral portions 140A of an insulating layer 140 as well as a crack reducing interlayer 145 within the insulating layer 140 for preventing or reducing the propagation of cracks through the insulating layer 140. The combination of both a crack reducing interlayer 145 and a trench 175 may further reduce the possibility of unwanted metal migration in the structure.

[0271] FIG. 66C is a cross sectional view of an LED structure 100H' according to still further embodiments. In the LED structure 100H', the crack reducing interlayer 145 is set back from the sidewalls of the trench 175. That is, the crack reducing interlayer 145 is insulated from the sidewalls of the trench 175 by portions of the insulating layer 140.

[0272] Various embodiments have been described herein in connection with operational flowcharts including flowchart blocks. It should be noted that in some alternate embodiments, the functions/acts noted in the blocks may occur out of the order noted in the flowcharts unless expressly stated to the contrary herein. For example, two blocks shown in succession may in fact be executed substantially concurrently or the blocks may sometimes be executed in the reverse order, depending upon the functionality/acts involved, unless expressly stated to the contrary herein. Moreover, the functionality of a given block of the flowcharts may be separated into multiple blocks and/or the functionality of two or more blocks may be at least partially integrated. Finally, other blocks may be added/inserted between the blocks that are illustrated.

[0273] Many different embodiments have been disclosed herein, in connection with the above description and the drawings. It will be understood that it would be unduly repetitious and obfuscating to literally describe and illustrate every combination and subcombination of these embodiments. Accordingly, the present specification, including the drawings, shall be construed to constitute a complete written description of all combinations and subcombinations of the embodiments described herein, and of the manner and process of making and using them, and shall support claims to any such combination or subcombination.

[0274] In the specification, there have been disclosed embodiments of the invention and, although specific terms are employed, they are used in a generic and descriptive sense only and not for purposes of limitation. The following claims are provided to ensure that the present application meets all statutory requirements as a priority application in all jurisdictions and shall not be construed as setting forth the entire scope of the present invention.

1.-20. (canceled)

21. A method for fabricating a lighting device, the method comprising:

growing epitaxial layers over an inner face of a growth substrate and defining a plurality of trenches in the epitaxial layers to produce an array of LEDs;

providing a plurality of anode contacts and a plurality of cathode contacts in conductive electrical communication with the array of LEDs;

mounting the array of LEDs over a carrier, including establishing conductive electrical communication between the plurality of anode contacts and a plurality



of anode pads of the carrier, and establishing conductive electrical communication between the plurality of cathode contacts and a plurality of cathode pads of the carrier; and

processing at least one light extraction surface including an outer face of the growth substrate to shape and/or texture the at least one light extraction surface, wherein the processing of the at least one light extraction surface is performed after the mounting of the array of LEDs over the carrier.

**22.** The method of claim **21**, wherein the processing of the at least one light extraction surface comprises shaping the light extraction surface to bevel portions of the at least one light extraction surface.

**23.** The method of claim **22**, wherein the shaping of the light extraction surface to bevel portions of the at least one light extraction surface comprises forming bevels with a saw blade or laser.

**24.** The method of claim **22**, wherein the shaping of the light extraction surface to bevel portions of the at least one light extraction surface comprises forming bevels by wet and/or dry etching.

**25.** The method of claim **22**, wherein the shaping of the light extraction surface to bevel portions of the at least one light extraction surface comprises beveling areas of the substrate between individual LEDs of the array of LEDs.

**26.** The method of claim **22**, wherein the shaping of the light extraction surface to bevel portions of the at least one light extraction surface forms a plurality of facets on the at least one light extraction surface.

**27.** The method of claim **21**, wherein the processing of the at least one light extraction surface comprises texturing the at least one light extraction surface.

**28.** The method of claim **27**, wherein the texturing of the at least one light extraction surface comprises etching the at least one light extraction surface.

**29.** The method of claim **27**, wherein the texturing of the at least one light extraction surface comprises texturing outer faces and sidewalls of LEDs of the array of LEDs.

**30.** The method of claim **21**, wherein the processing of the at least one light extraction surface further comprises thinning the growth substrate.

**31.** The method of claim **30**, wherein the thinning of the growth substrate is performed prior to the processing to shape and/or texture the at least one light extraction surface.

**32.** The method of claim **21**, further comprising defining a plurality of recesses in the growth substrate in a direction extending from the outer face toward the inner face.

**33.** The method of claim **21**, further comprising applying a wavelength conversion material on or over the at least one light extraction surface.

**34.** The method of claim **33**, wherein the applying of a wavelength conversion material on or over the at least one light extraction surface comprises applying wavelength conversion material by spraying.

**35.** The method of claim **33**, wherein the applying of a wavelength conversion material on or over the at least one light extraction surface comprises applying wavelength conversion material over outer faces and sidewalls of LEDs of the array of LEDs.

**36.** The method of claim **33**, wherein the wavelength material is applied into trenches between LEDs of the array of LEDs.

**37.** The method of claim **21**, wherein the array of LEDs is embodied in an LED wafer.

**38.** The method of claim **21**, further comprising electrically connecting at least some LEDs of the array of LEDs in series and/or in parallel.

**39.** The method of claim **21**, further comprising singulating some LEDs of the array of LEDs to form a plurality of LED chips.

**40.** A lighting device produced by the method of claim **21**.

\* \* \* \* \*