US011271023B2

(12) **United States Patent**
Stanton

(10) **Patent No.: US 11,271,023 B2**
(45) **Date of Patent: Mar. 8, 2022**

(54) **QUANTUM WAVEGUIDE INFRARED PHOTODETECTOR**

(71) Applicant: **Government of the United States of America, as represented by the Secretary of Commerce**, Gaithersburg, MD (US)

(72) Inventor: **Eric John Stanton**, Boulder, CO (US)

(73) Assignee: **GOVERNMENT OF THE UNITED STATES OF AMERICA, AS REPRESENTED BY THE SECRETARY OF COMMERCE**, Gaithersburg, MD (US)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 29 days.

(21) Appl. No.: **16/919,515**

(22) Filed: **Jul. 2, 2020**

(65) **Prior Publication Data**

US 2021/0028214 A1 Jan. 28, 2021

Related U.S. Application Data

(60) Provisional application No. 62/877,932, filed on Jul. 24, 2019.

(51) **Int. Cl.**

H01L 31/103	(2006.01)
H01L 27/146	(2006.01)
H01L 31/0232	(2014.01)
H01L 31/0352	(2006.01)

(52) **U.S. Cl.**
CPC .. ***H01L 27/14625*** (2013.01); ***H01L 27/14669*** (2013.01); ***H01L 31/02327*** (2013.01); ***H01L 31/035218*** (2013.01)

(58) **Field of Classification Search**
CPC H01L 27/14625; H01L 31/02327; H01L 31/035218; H01L 27/14669; H01L 31/02027; H01L 31/101; H01L 31/102; H01L 31/103; H01L 31/107; H01L 31/1075
See application file for complete search history.

(56) **References Cited**

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2021/0210646 A1*	7/2021	Maros	H01L 31/03048

* cited by examiner

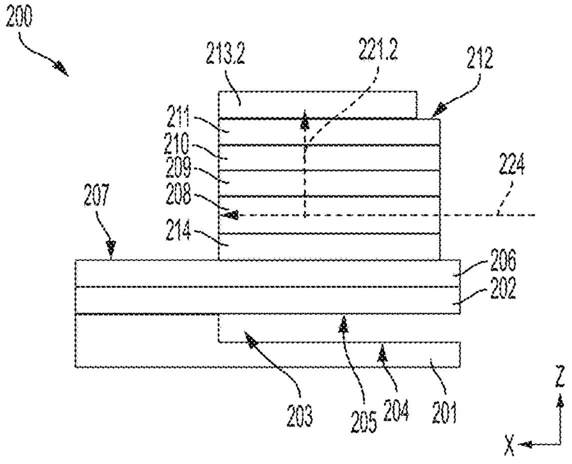
Primary Examiner — Eduardo A Rodela

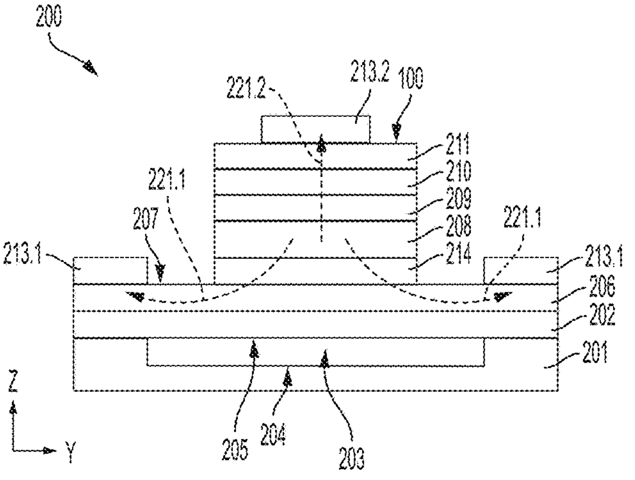
(74) *Attorney, Agent, or Firm* — Office of Chief Counsel for National Institute of Standards and Technology

(57) **ABSTRACT**

A quantum waveguide infrared photodetector includes: a photon absorption layer that receives infrared photons propagating longitudinally along a longitudinal length of the photon absorption layer, converts the infrared photons into electrons, and communicates the electrons to a conductor layer; a first conductor layer that receives a first electrical potential; and a second conductor layer that receives a second electrical potential, wherein electrons produced by the photon absorption layer are communicated from the photon absorption layer: to the first conductor layer when the first electrical potential is more positive than the second electrical potential, and to the second conductor layer when the second electrical potential is more positive than the first electrical potential, an electrical current produced by the electrons is proportional to an amount of absorption of the infrared photons in the photon absorption layer.

16 Claims, 31 Drawing Sheets





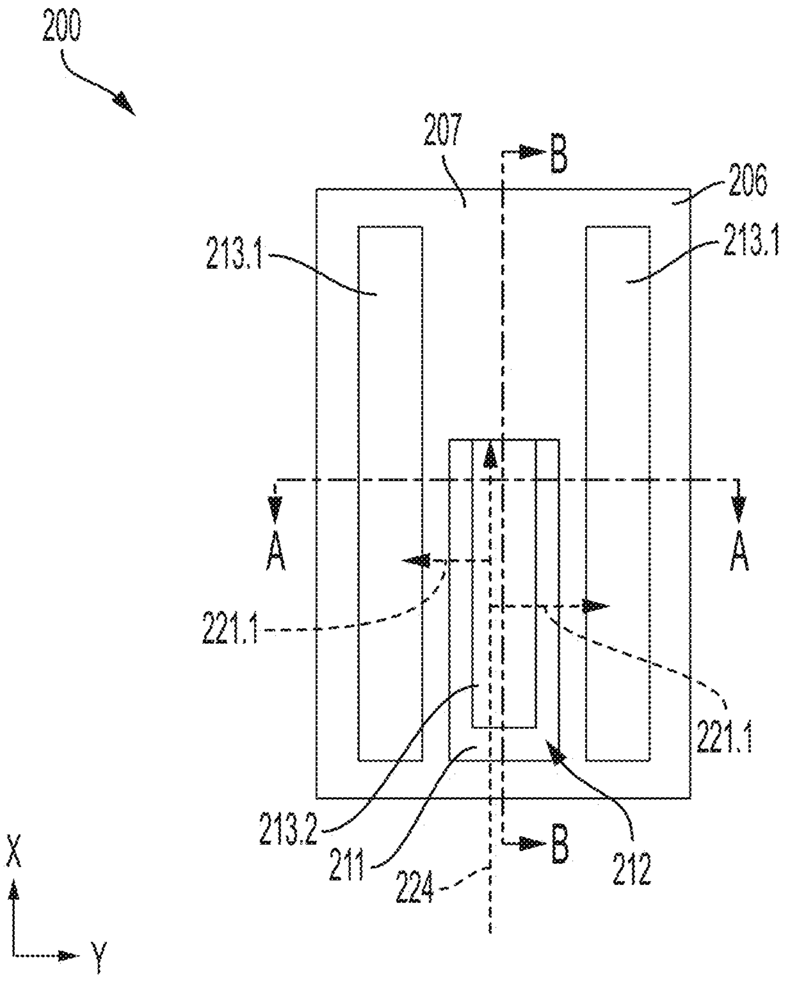
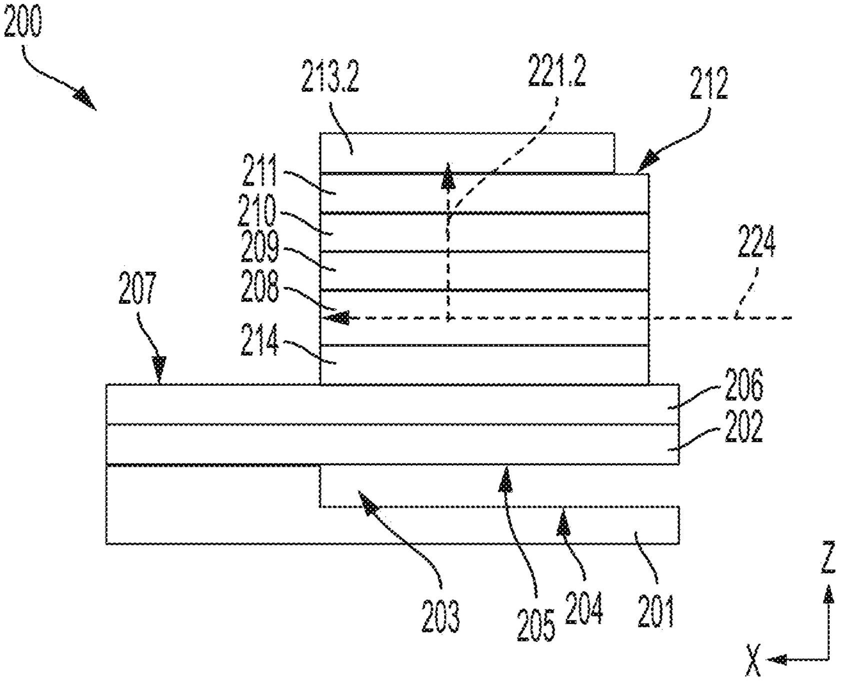


FIG. 1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213.2
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204
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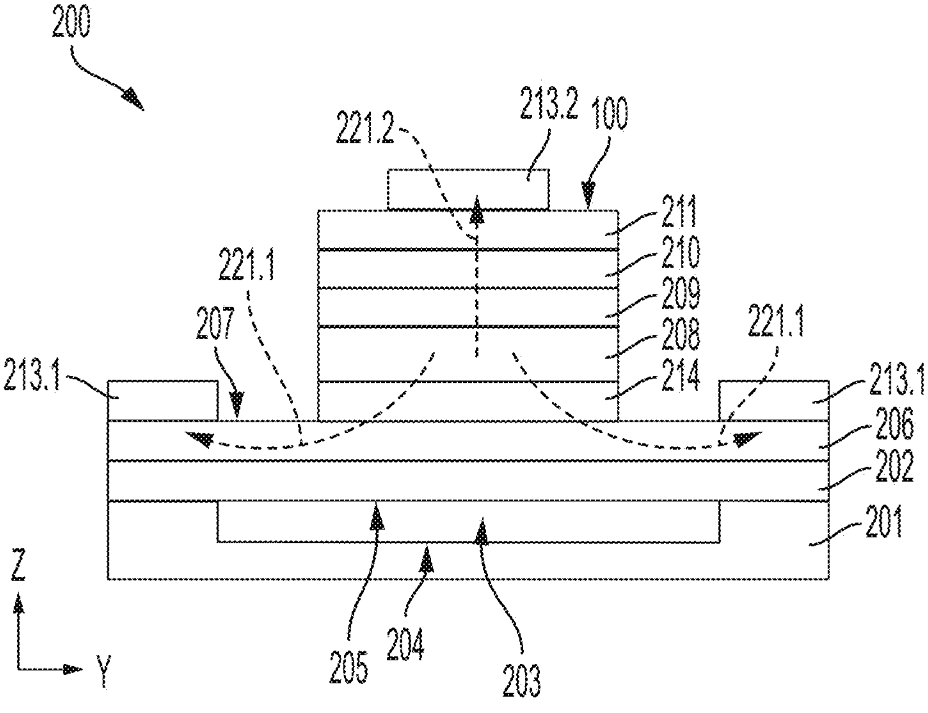
Z
X

FIG. 2A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Z
Y
205
204
203

FIG. 2B

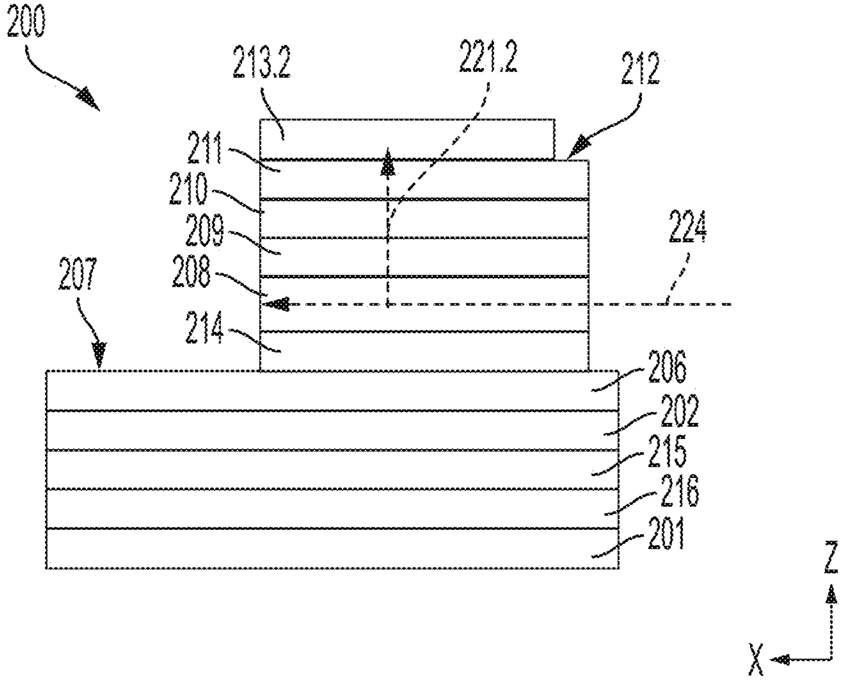
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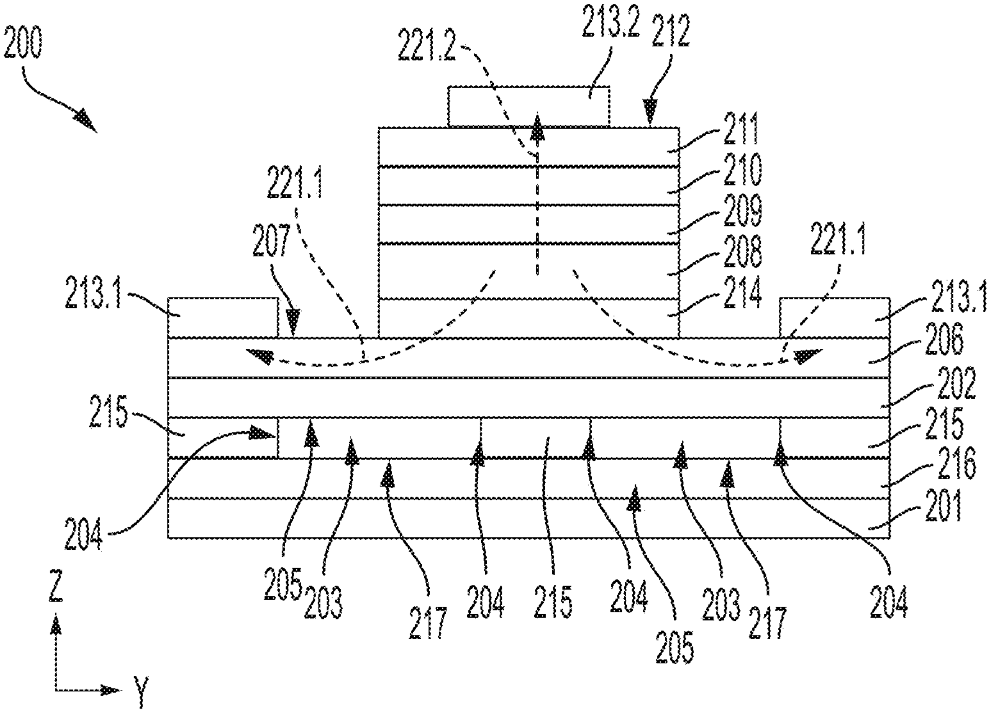
FIG. 3A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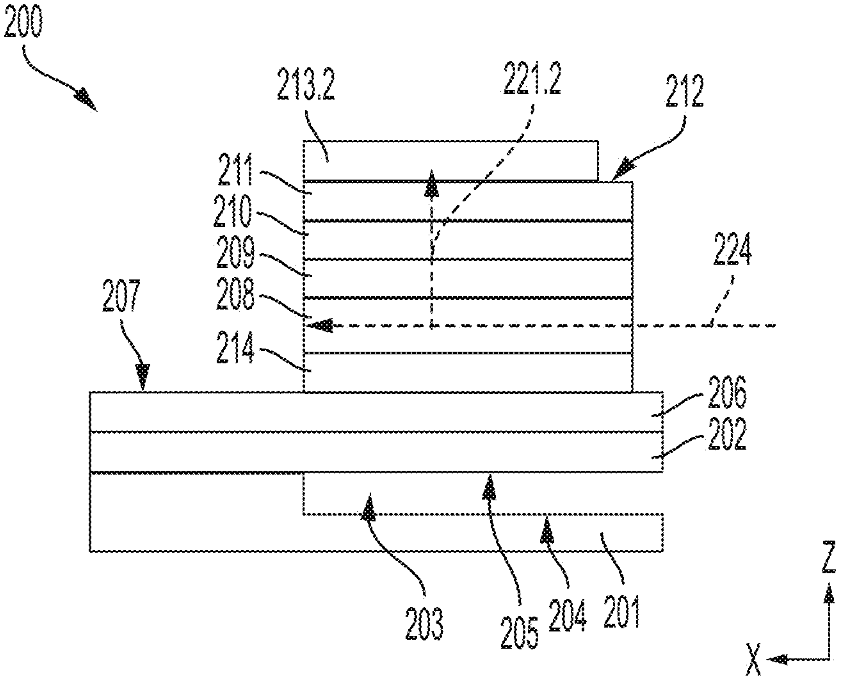
201
204
205
203
217
204
215
204
205
203
217
204
Z
Y

FIG. 3B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214
224
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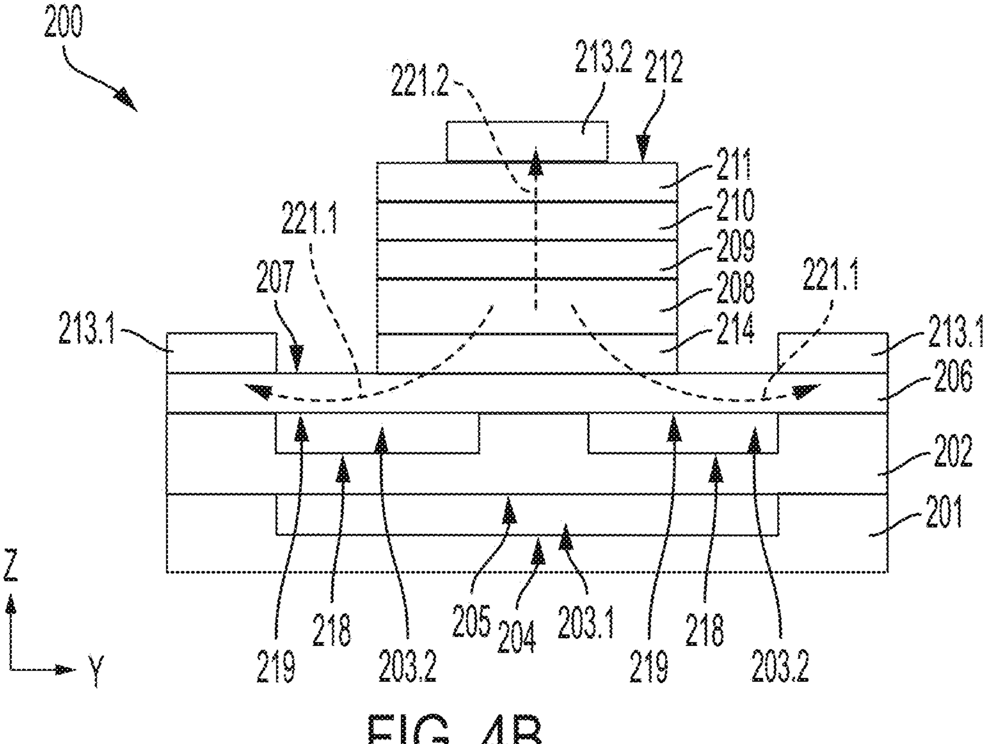
X

FIG. 4A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212
211
210
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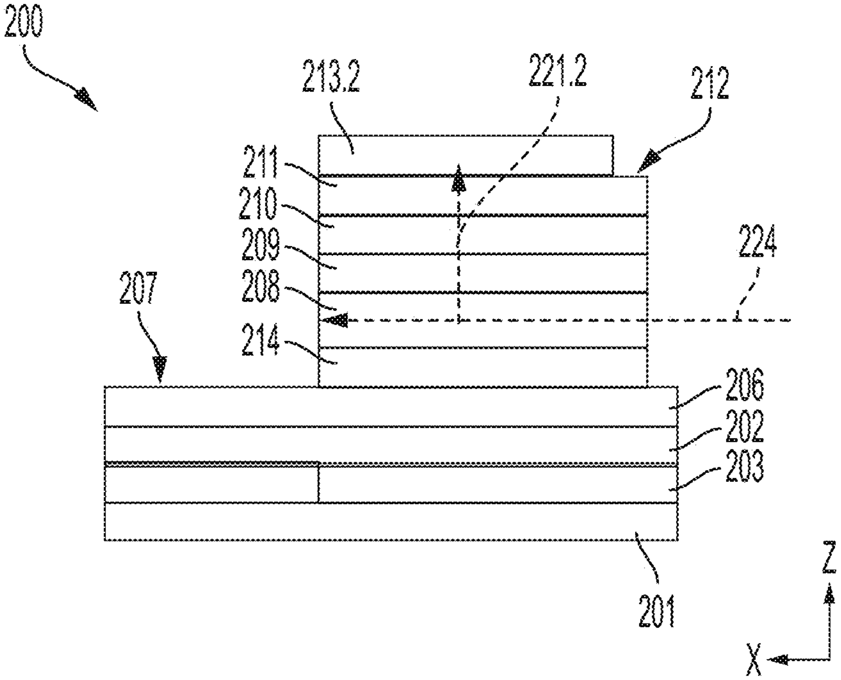
208
214
221.1
207
221.1
213.1
213.1
206
202
201
Z
Y
219
218
203.2
205
204
203.1
219
218
203.2

FIG. 4B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211
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209
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214
224
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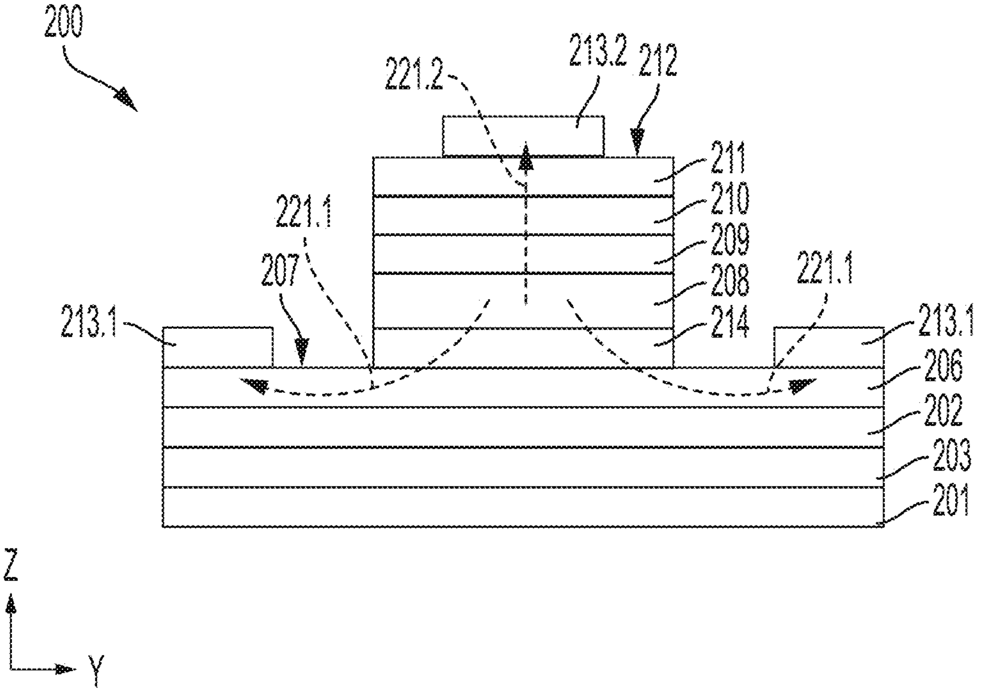
206
202
203
201
Z
X

FIG. 5A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213.2
212
211
210
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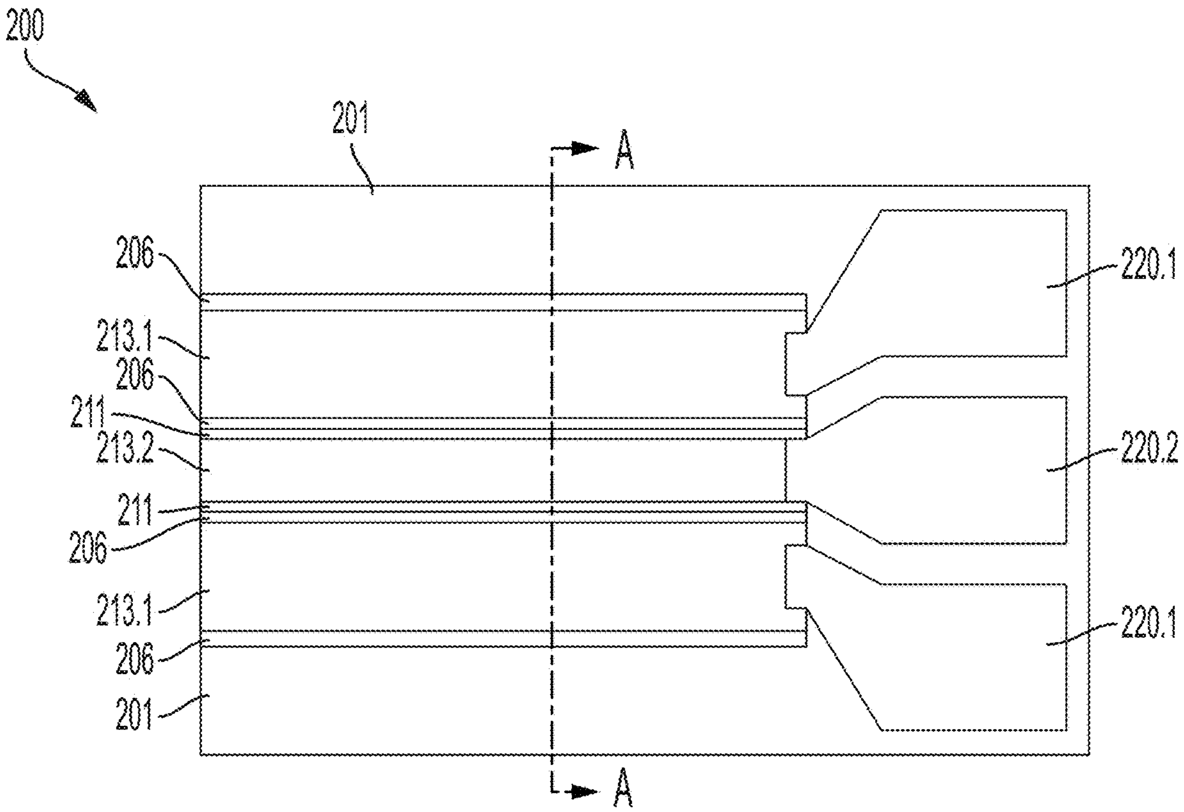
208
214
221.1
207
221.1
213.1
213.1
206
202
203
201
Z
Y

FIG. 5B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201
A
206
213.1
206
211
213.2
211
206
213.1
206
201
220.1
220.2
220.1
A

FIG. 6

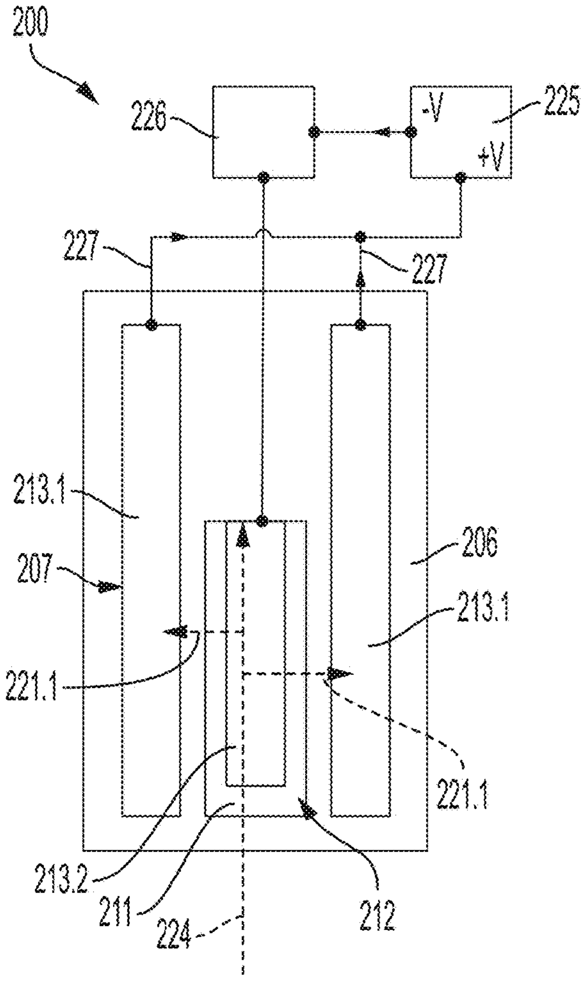
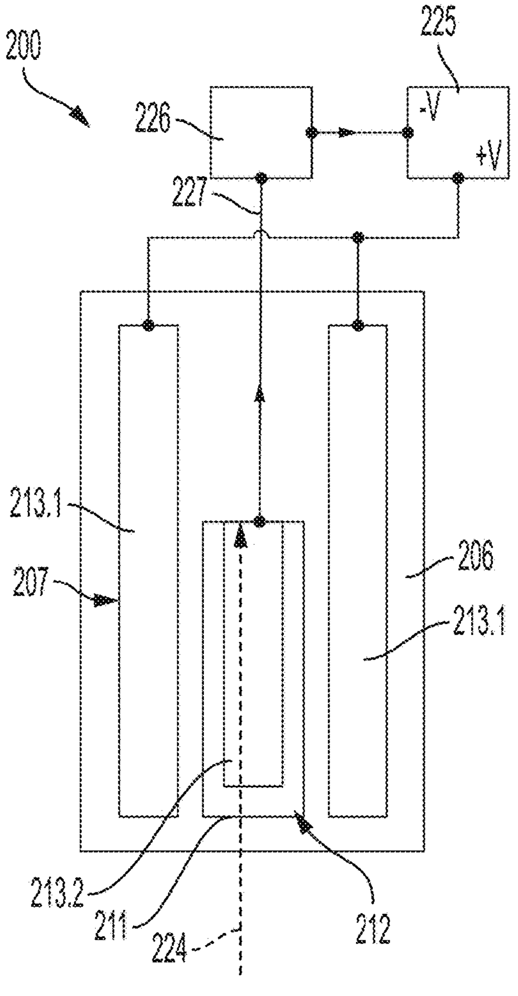

200
226
-V
+V
225
227
227
213.1
207
206
213.1
221.1
221.1
213.2
211
224
212

FIG. 7A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225
226
-V
+V
227
213.1
207
206
213.1
213.2
211
224
212

FIG. 7B

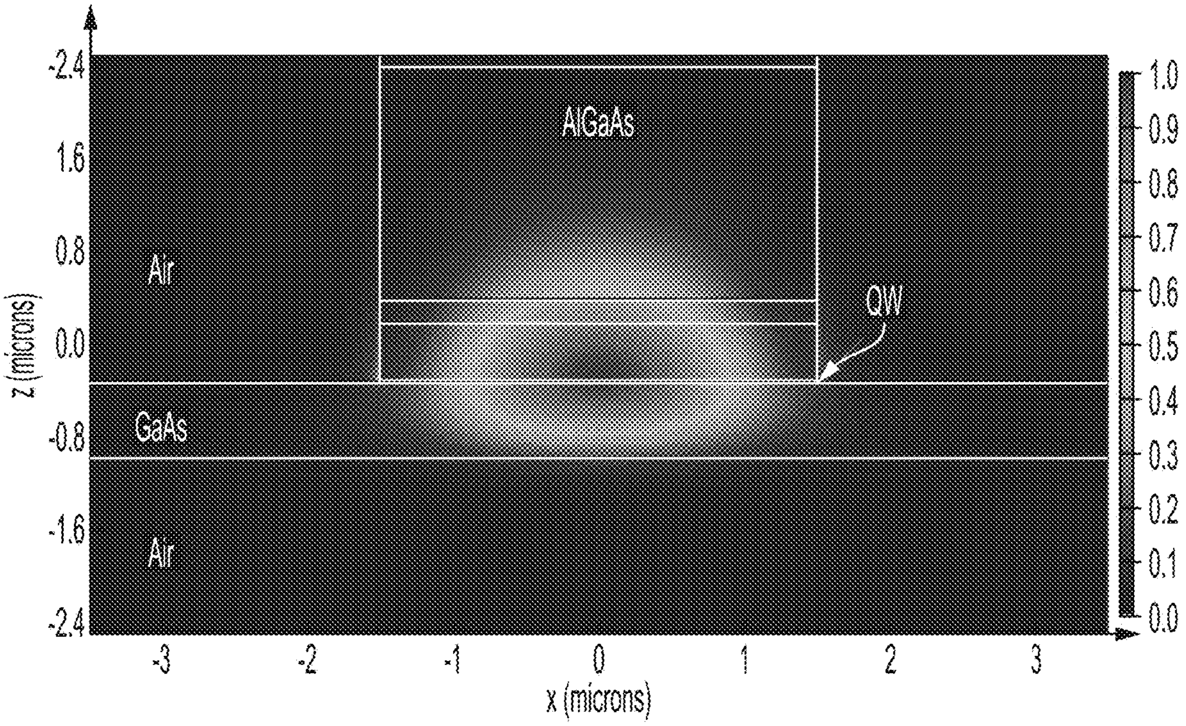

-2.4
1.6
0.8
0.0
-0.8
-1.6
-2.4
z (microns)
AlGaAs
Air
QW
GaAs
Air
-3
-2
-1
0
1
2
3
x (microns)
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0

FIG. 8

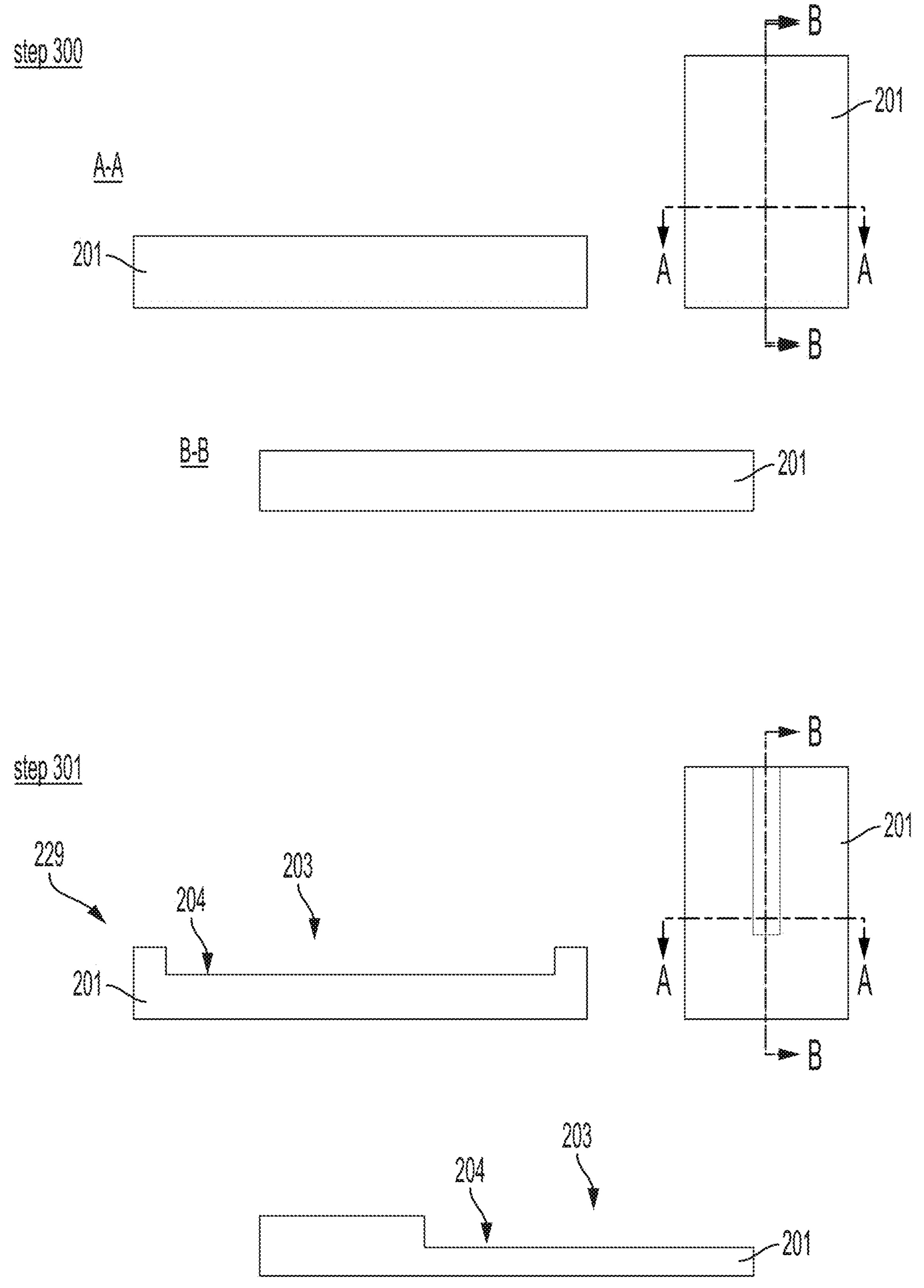
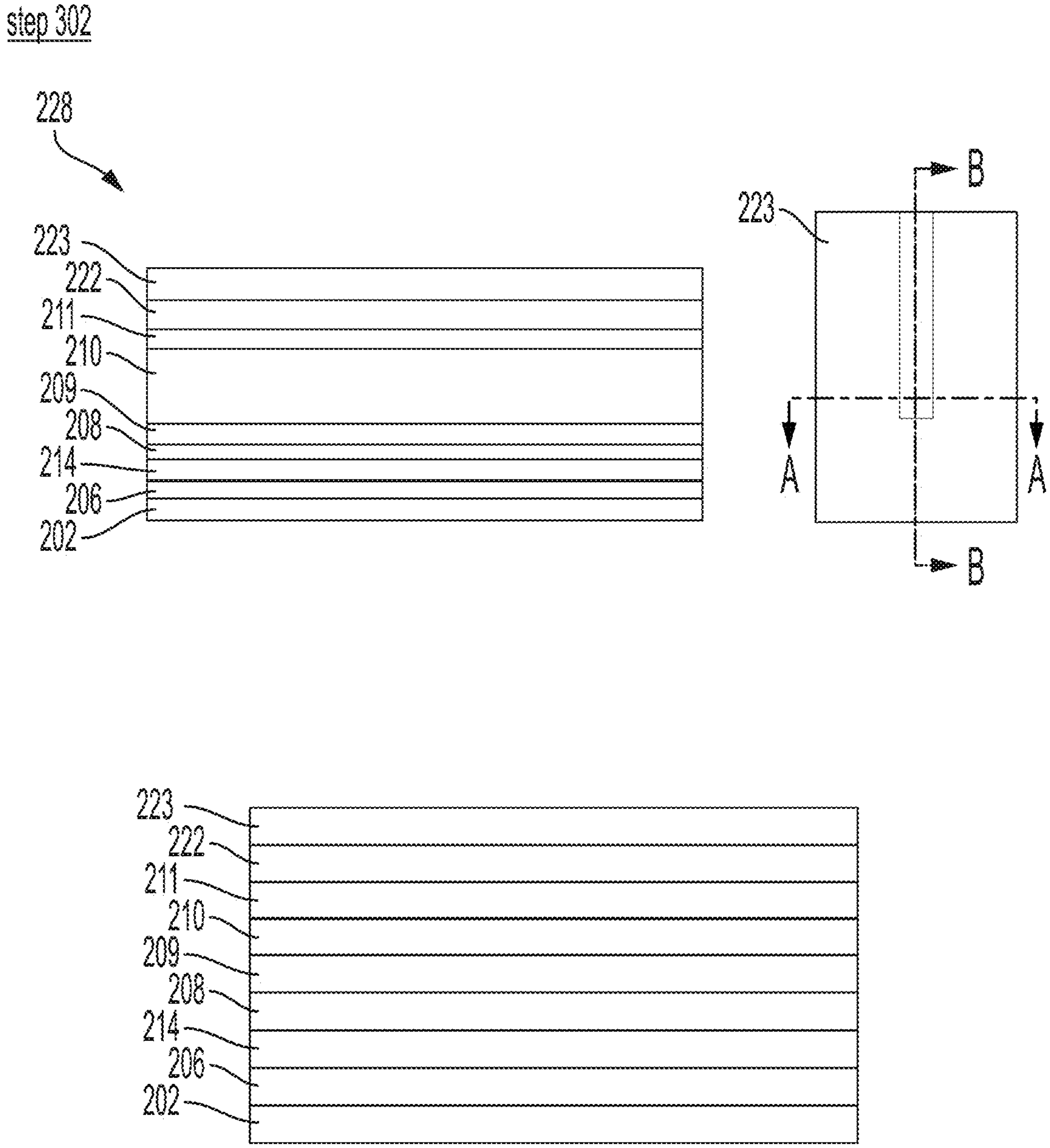

step 300
B
201
A-A
201
A
A
B
B-B
201
step 301
B
201
229
204
203
201
A
A
B
203
204
201

FIG. 9


step 302
228
223
222
211
210
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214
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202
223
B
A
A
B
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222
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210
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208
214
206
202

FIG. 10

step 303

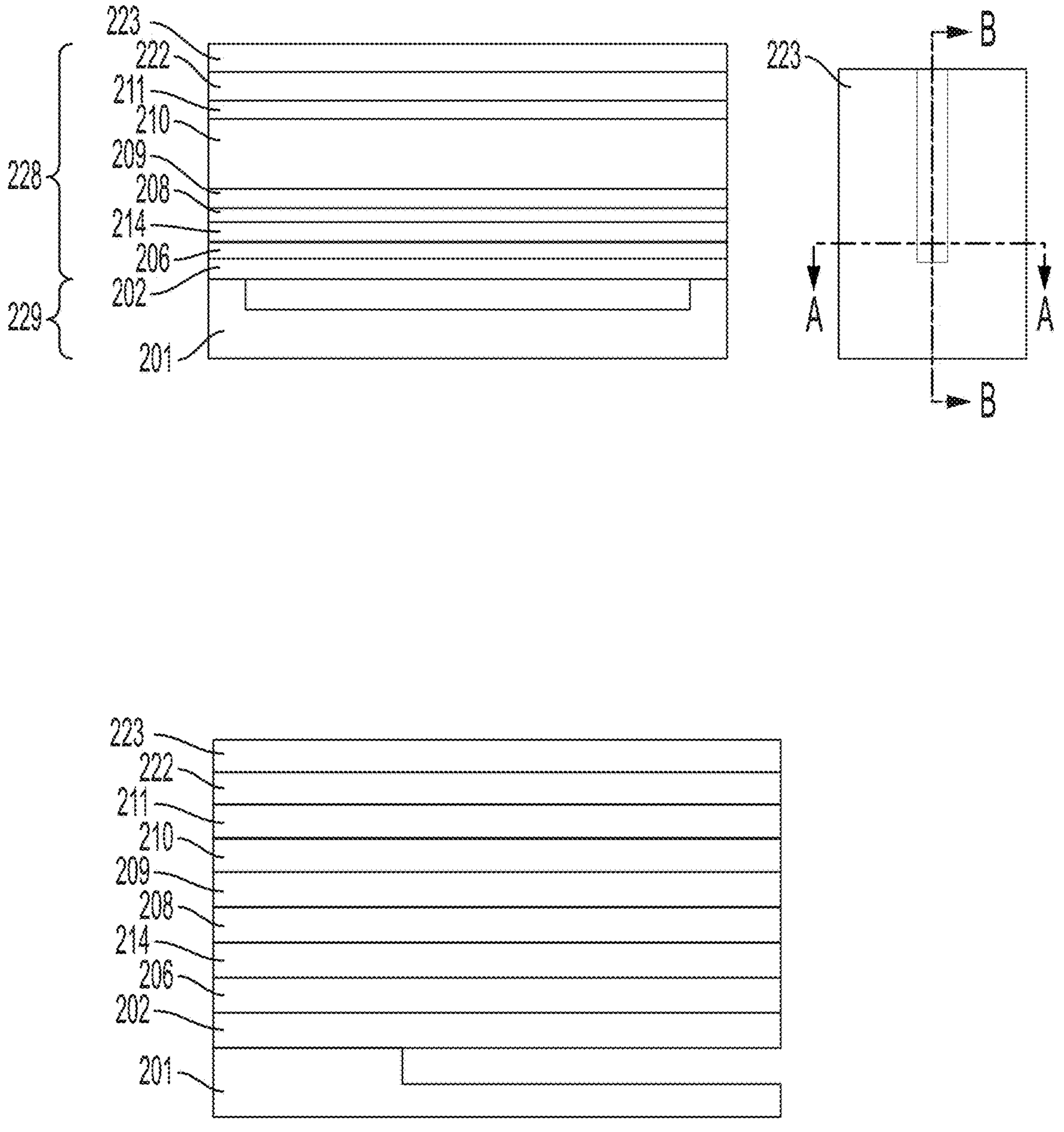

FIG. 11

step 304

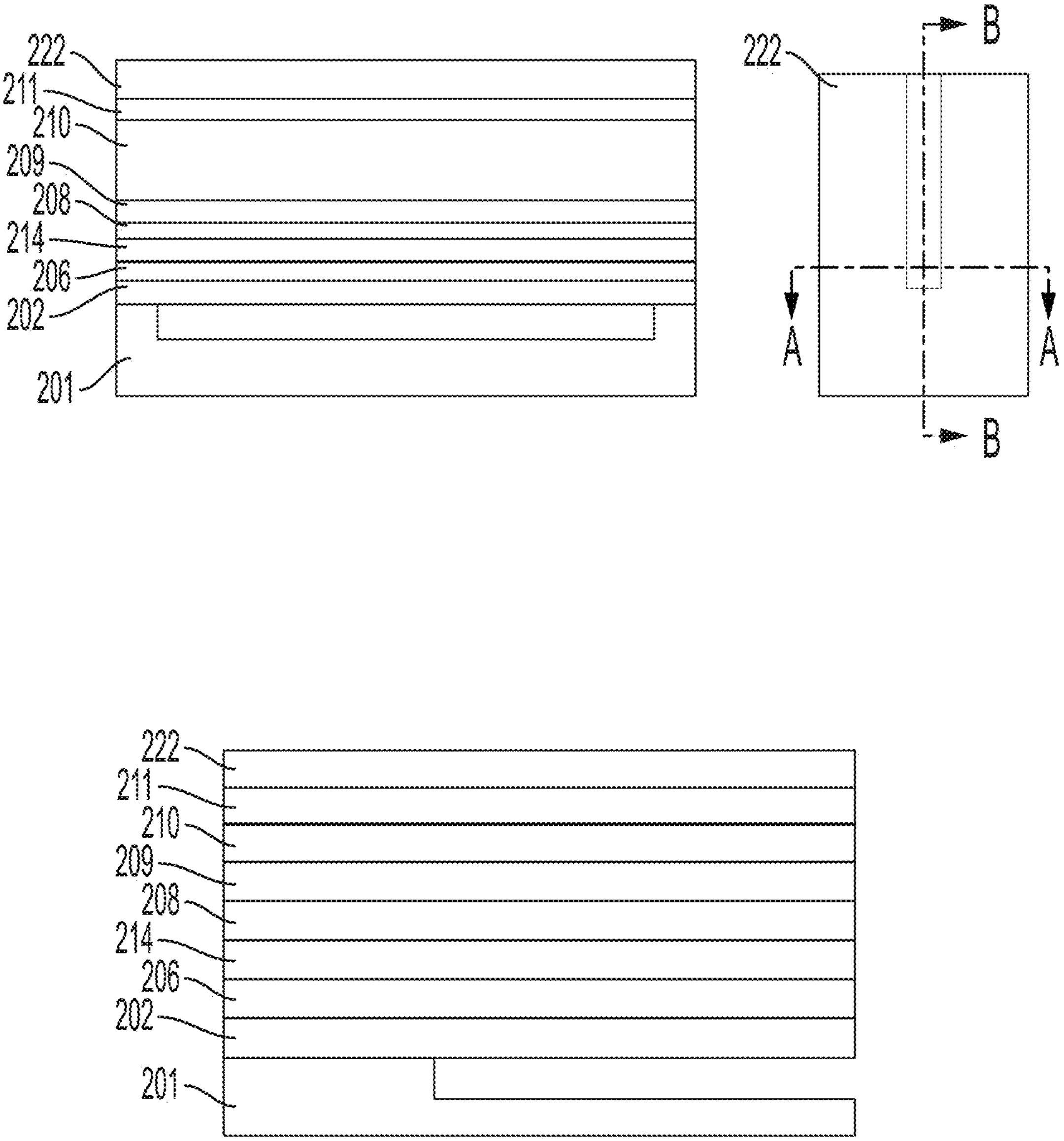

FIG. 12

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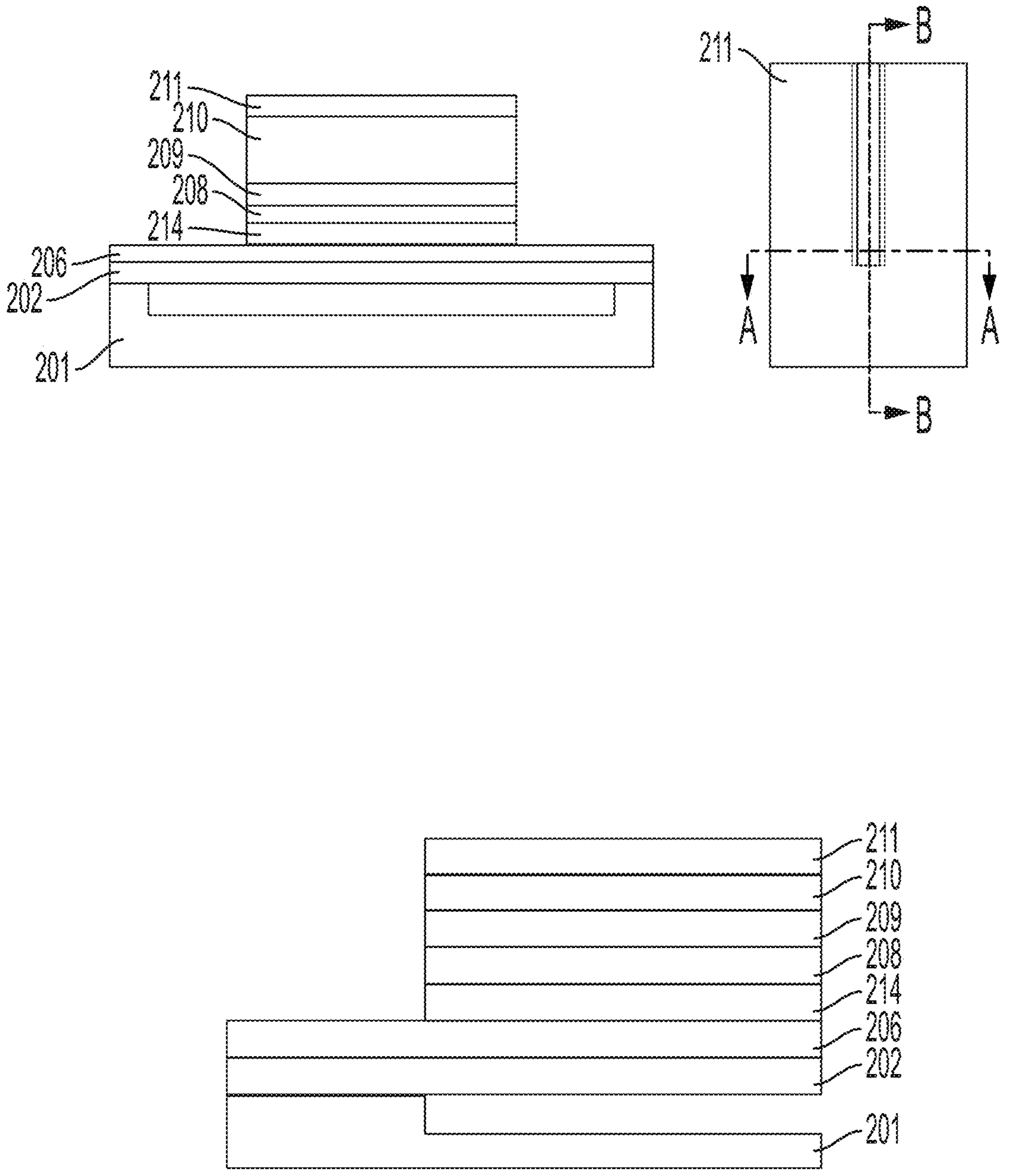


FIG. 13

step 306

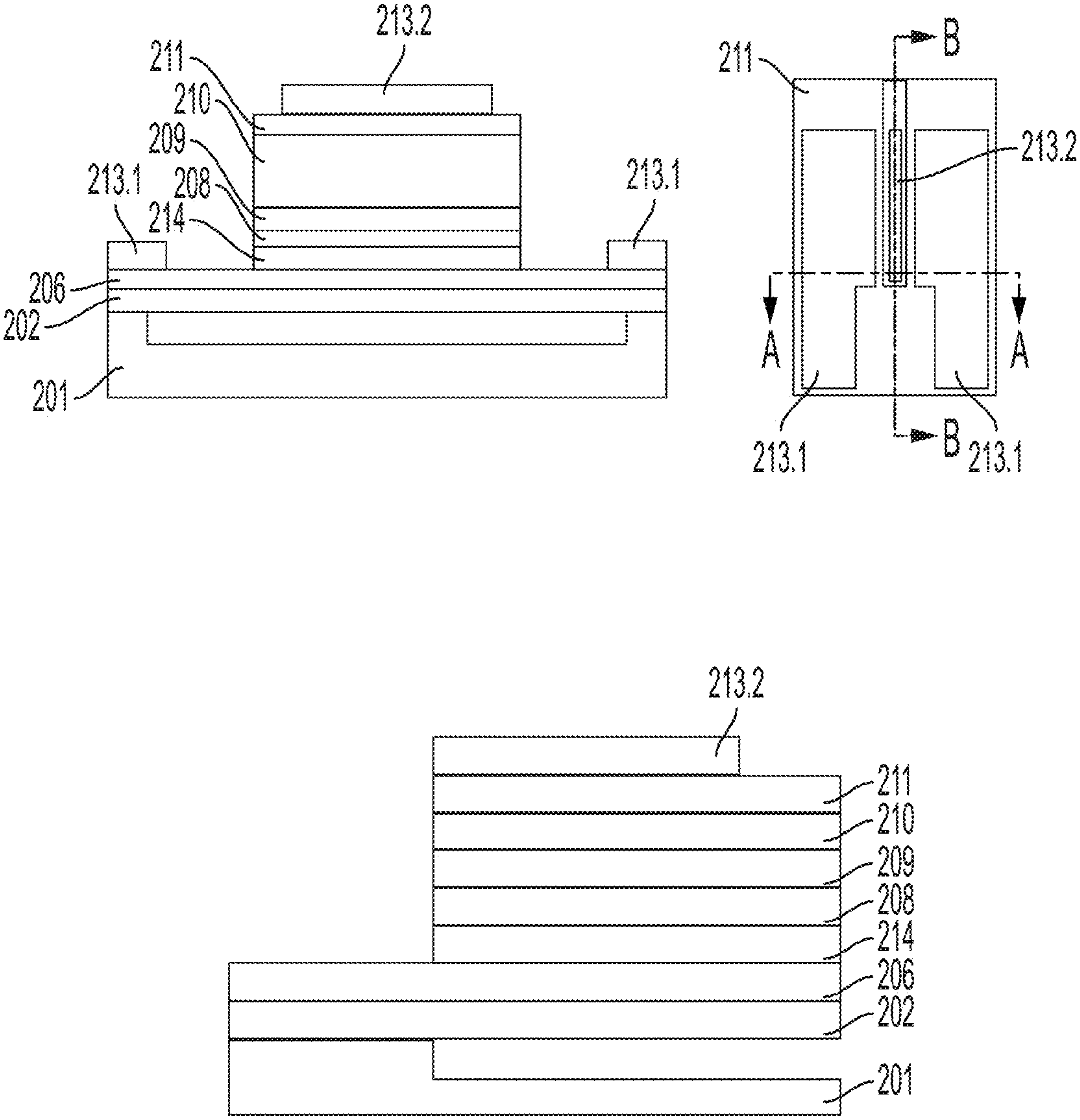


FIG. 14

step 307

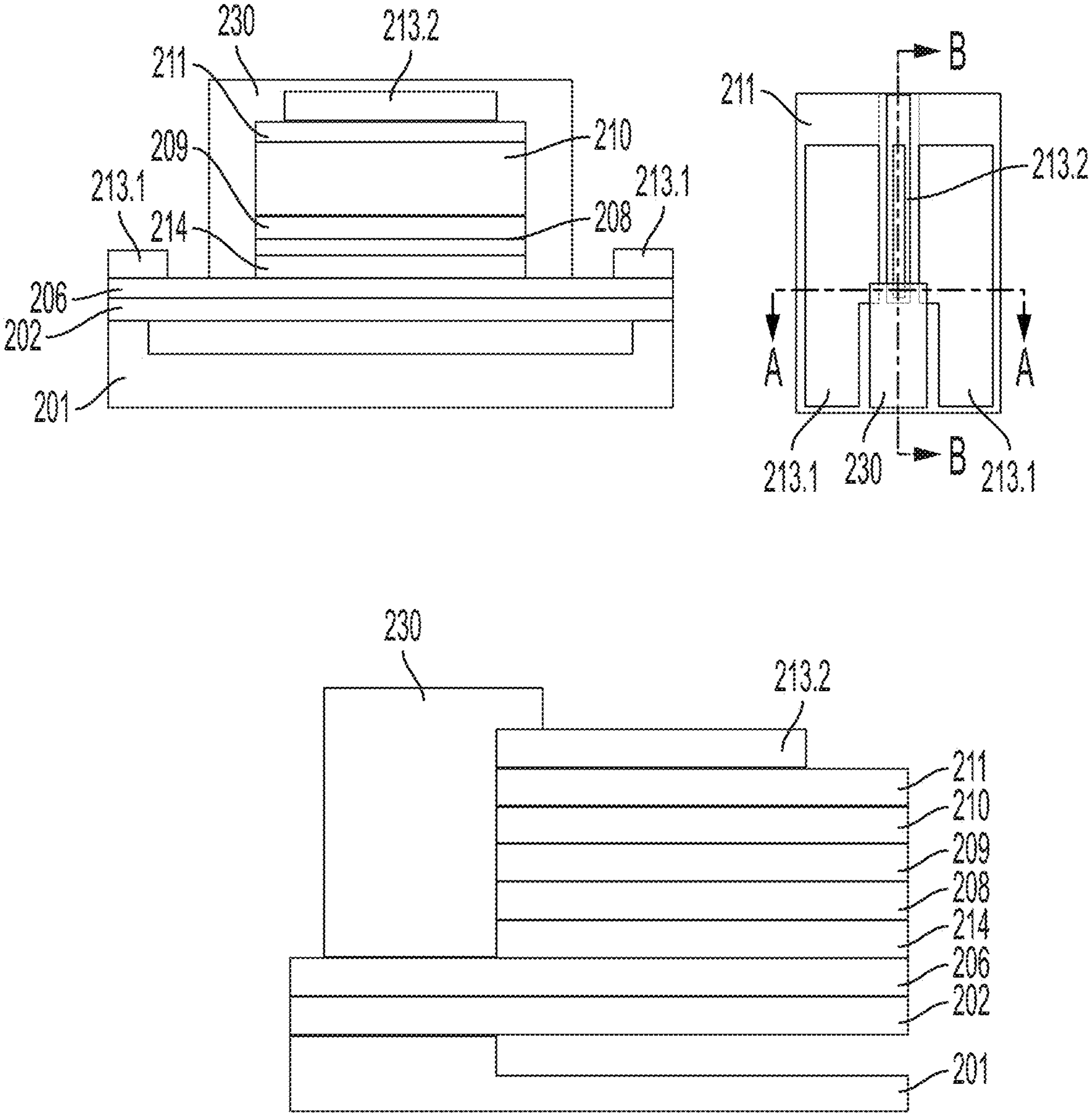


FIG. 15

step 308

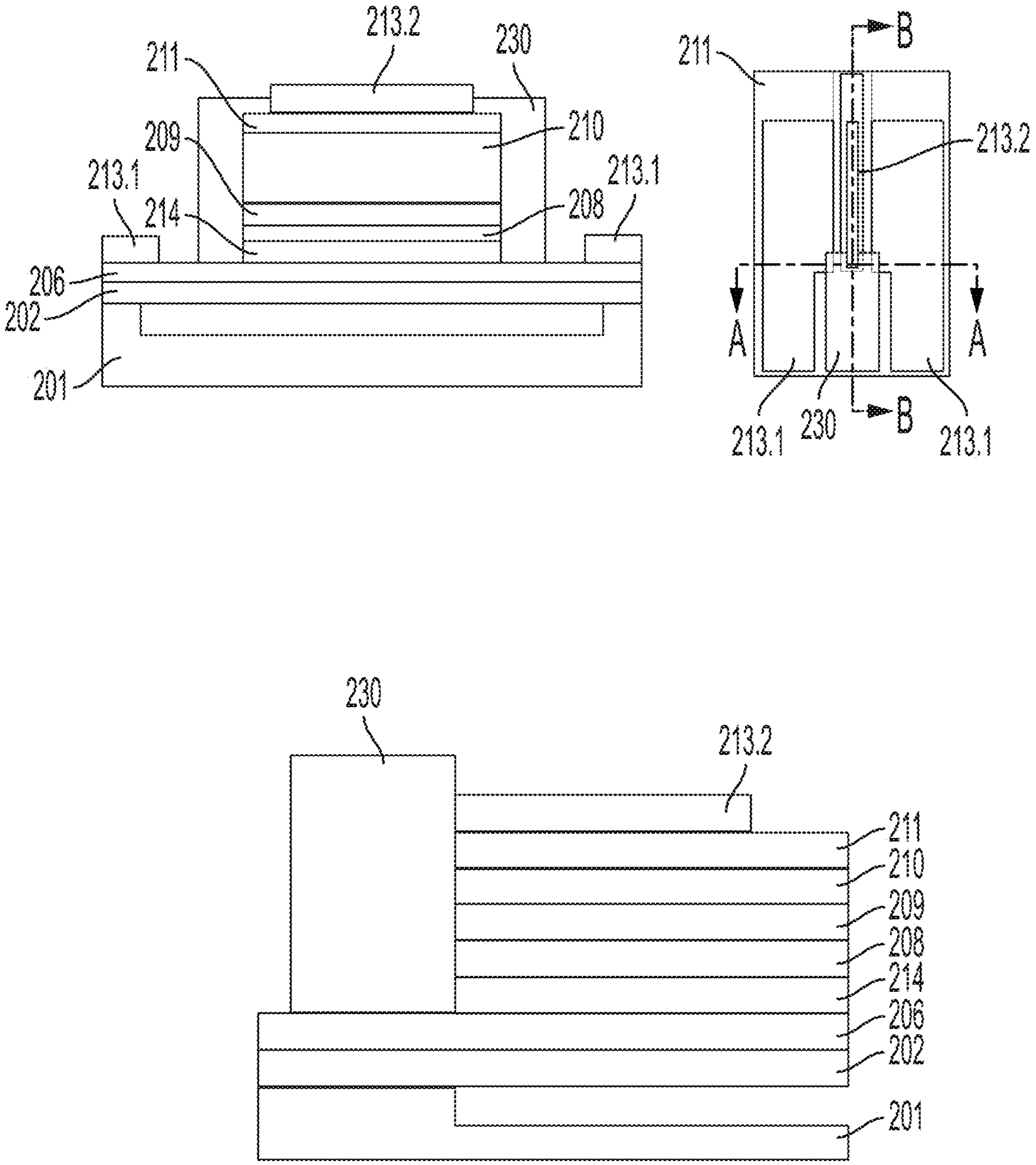


FIG. 16

step 309

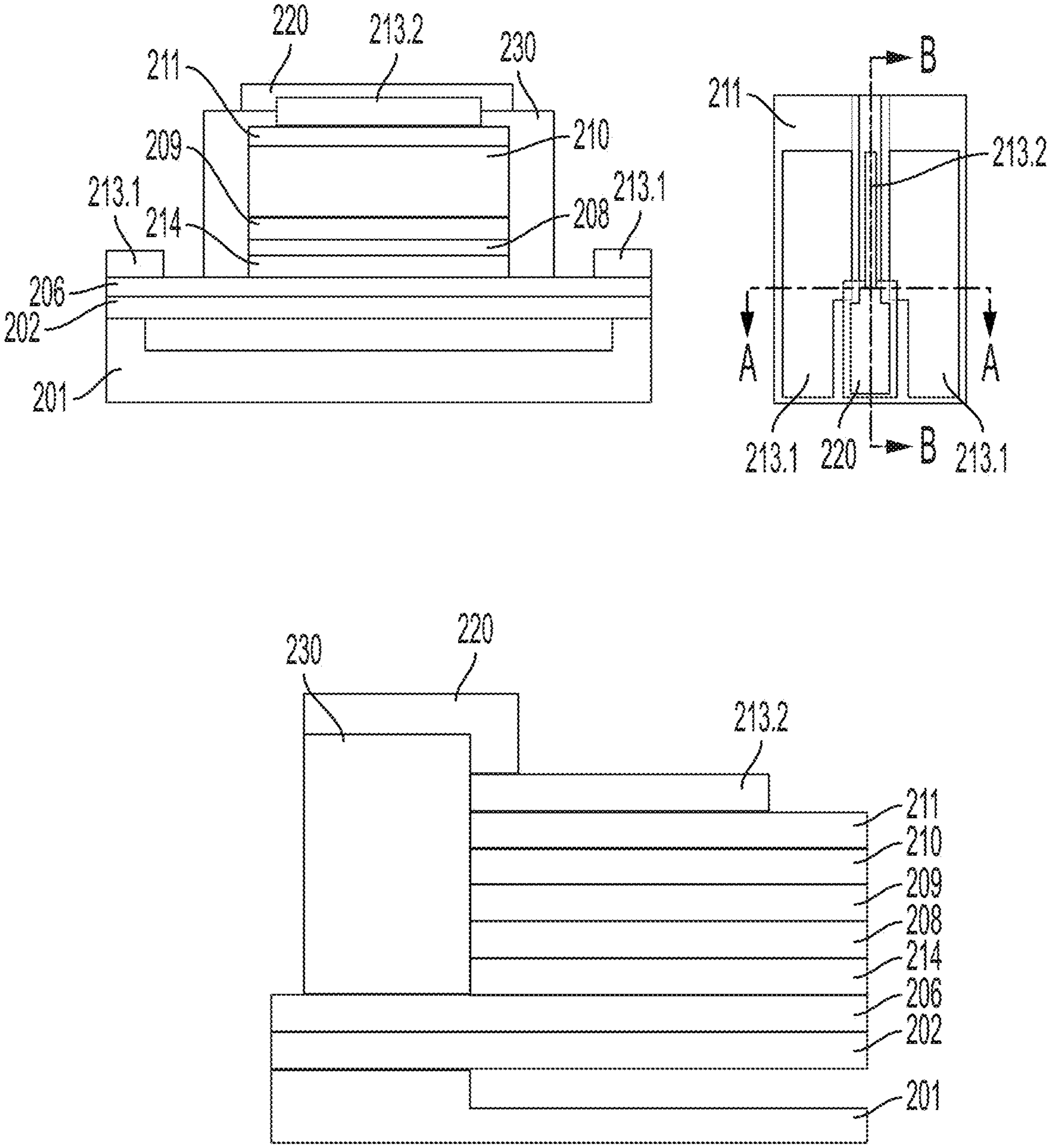


FIG. 17

step 310

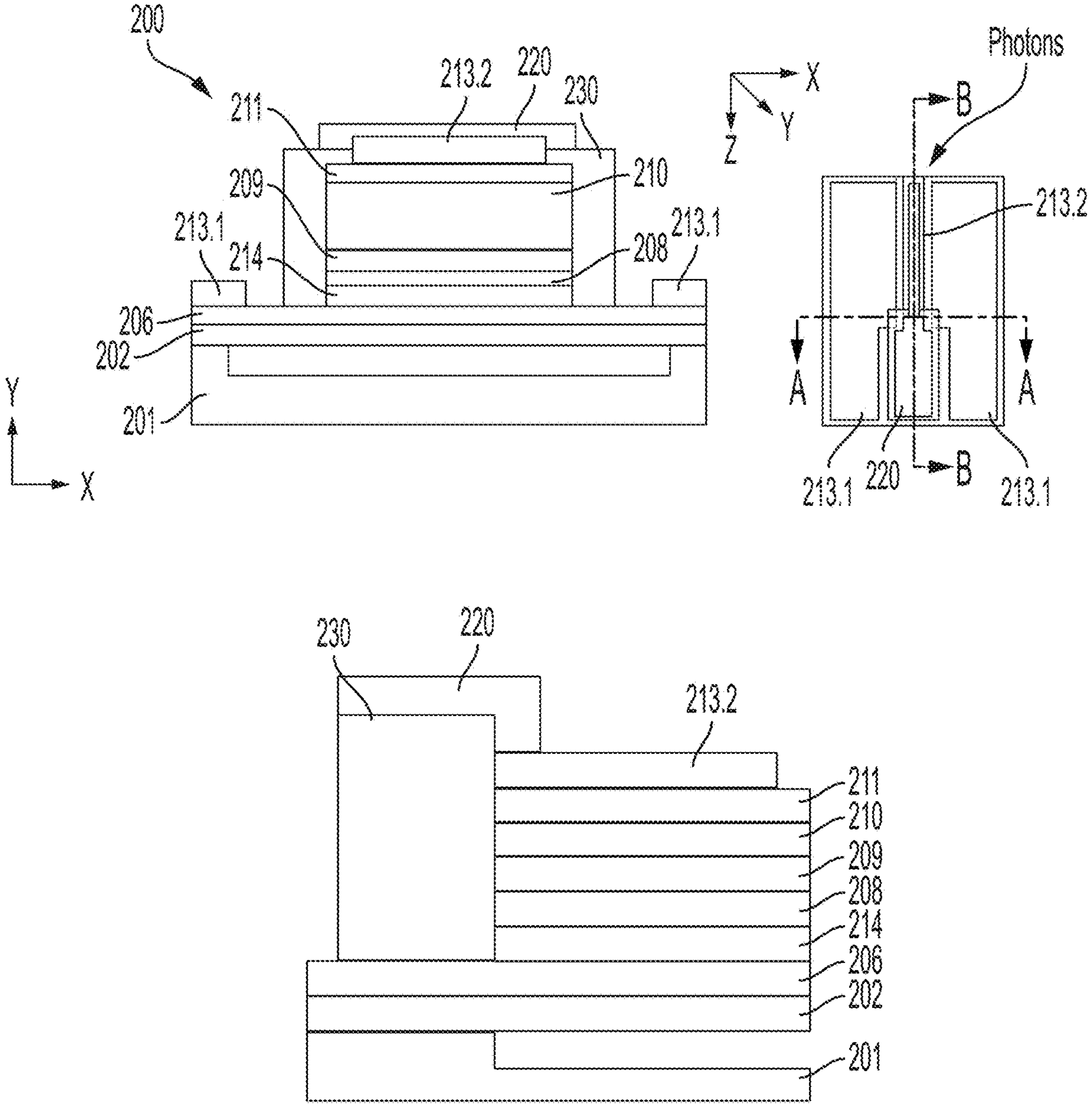


FIG. 18

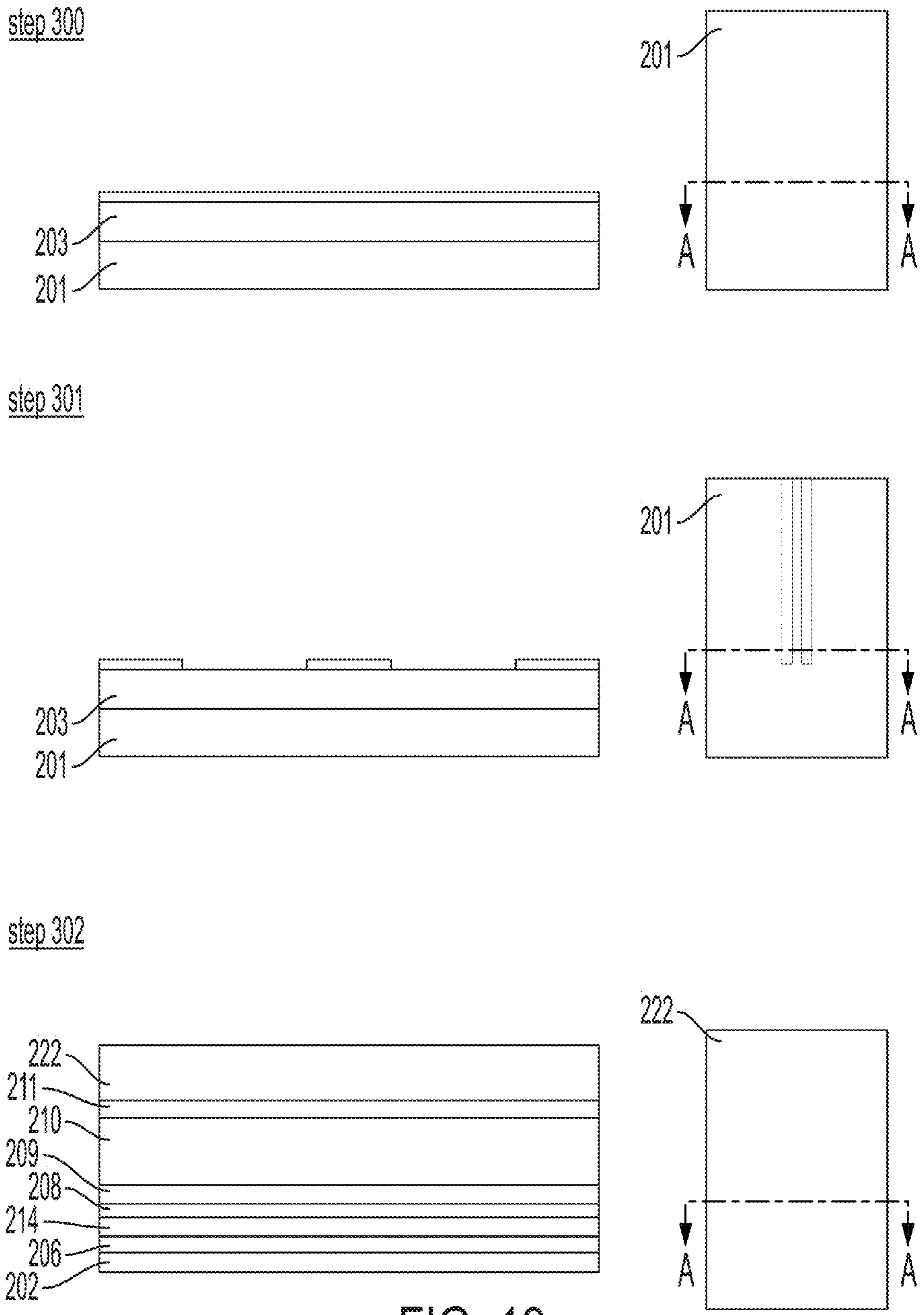
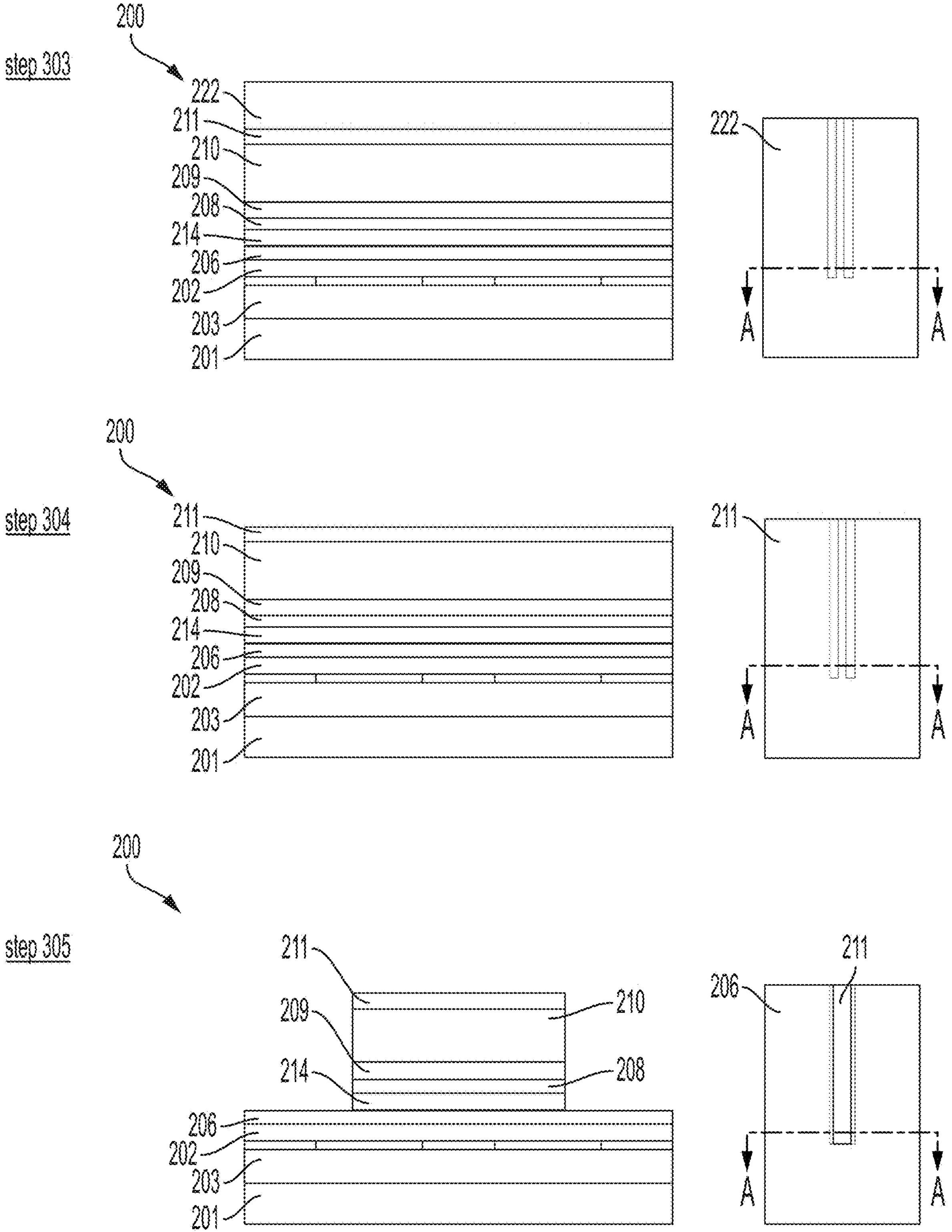

step 300
201
203
201
A
A
step 301
201
203
201
A
A
step 302
222
222
211
210
209
208
214
206
202
A
A

FIG. 19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222
A
A
step 304
200
211
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214
206
202
203
201
211
A
A
step 305
200
211
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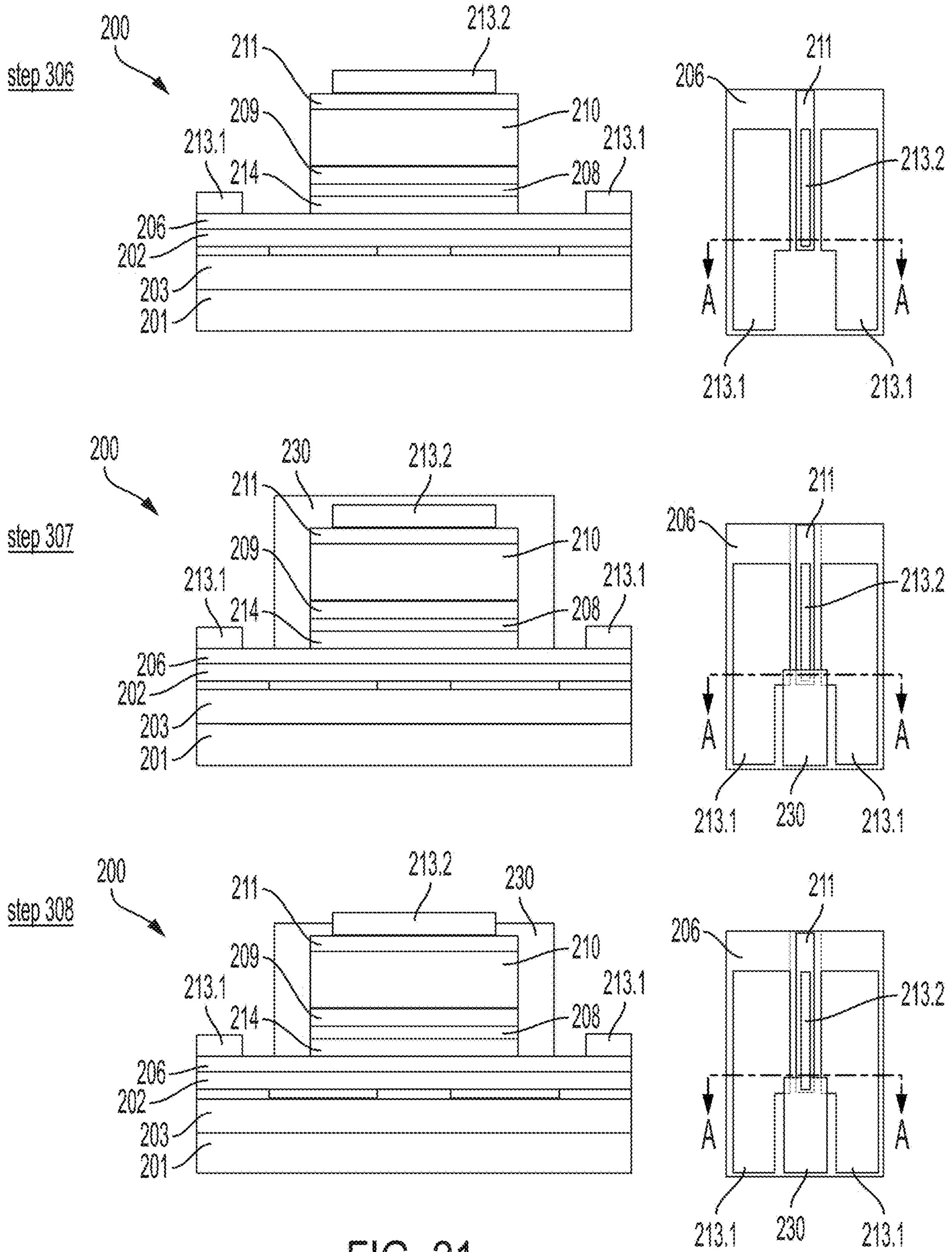
202
203
201
206
211
A
A

FIG. 20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213.1
206
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203
201
206
211
213.2
A
A
213.1
213.1
step 307
200
230
213.2
211
209
210
213.1
214
208
213.1
206
202
203
201
206
211
213.2
A
A
213.1
230
213.1
step 308
200
213.2
230
211
209
210
213.1
214
208
213.1
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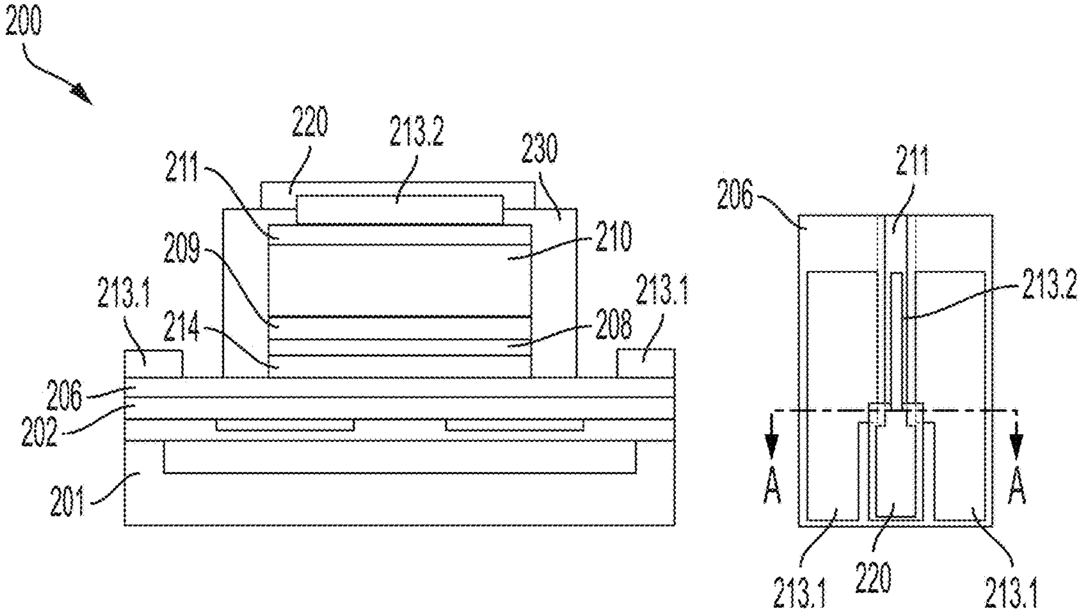
202
203
201
206
211
213.2
A
A
213.1
230
213.1

FIG. 21

step 309



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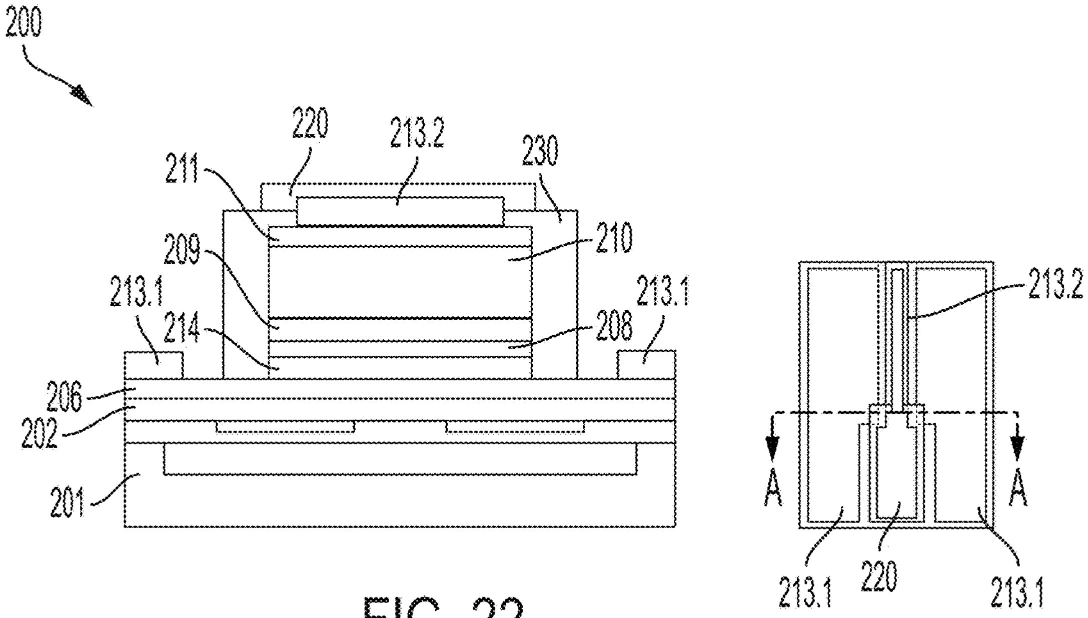

FIG. 22

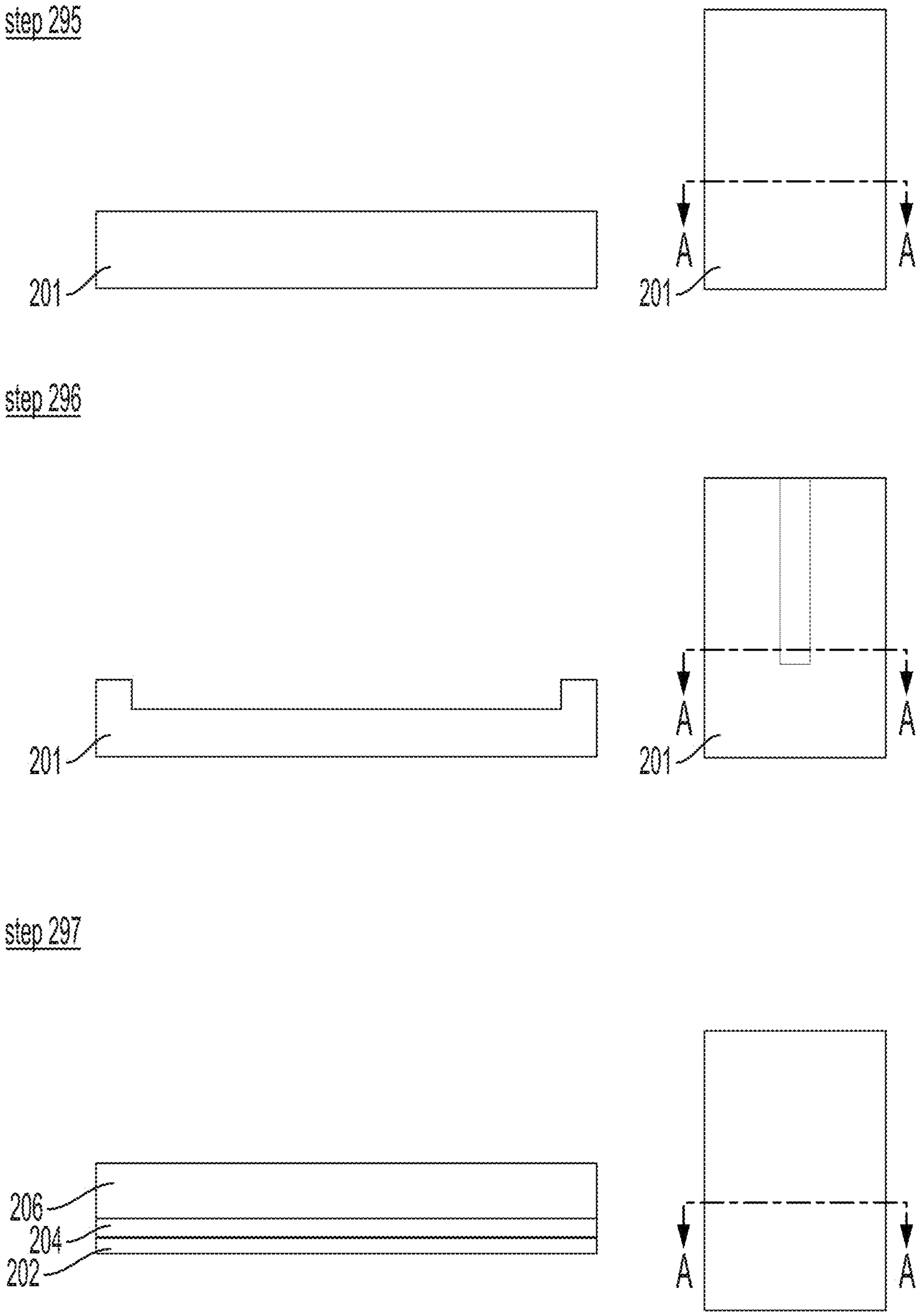

FIG. 23

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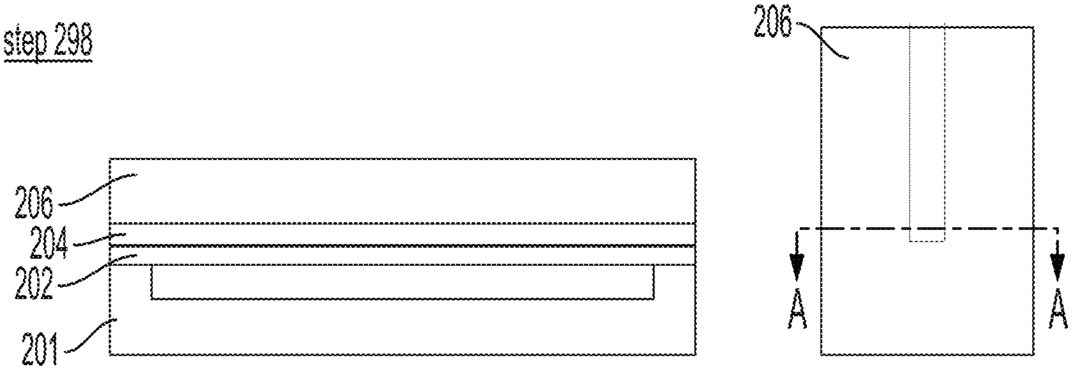

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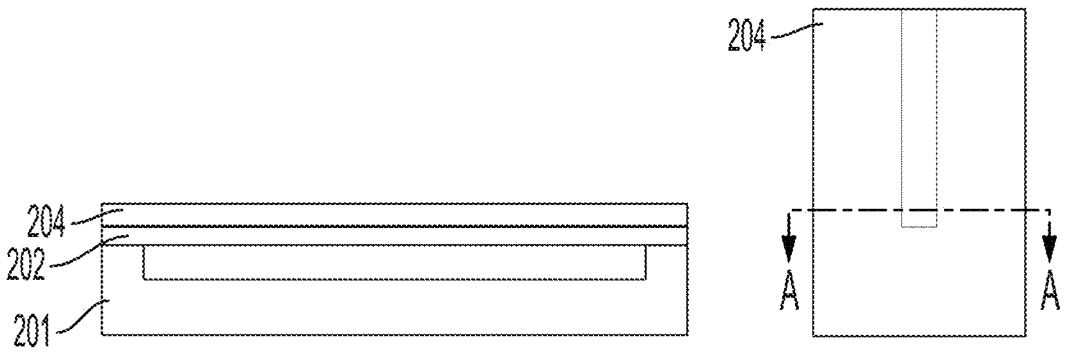

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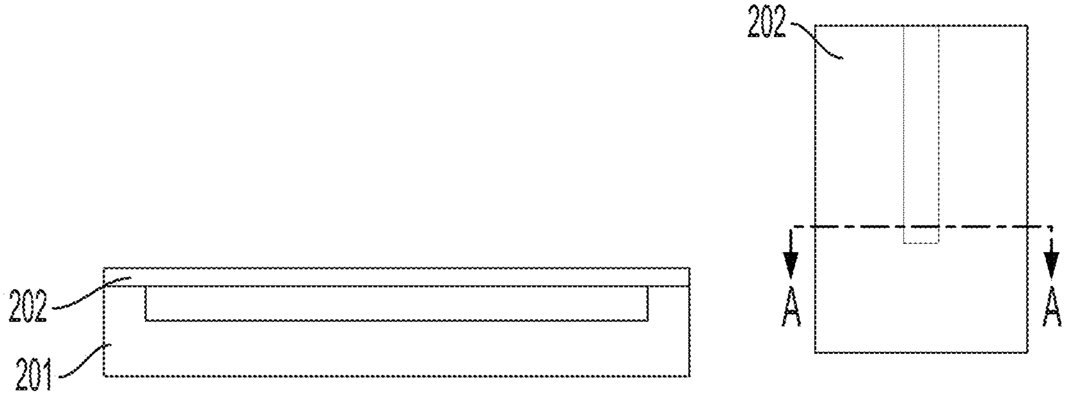

FIG. 24

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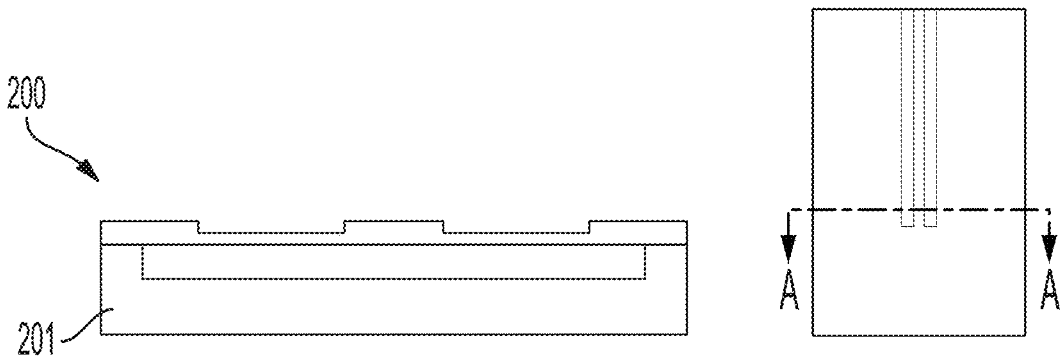

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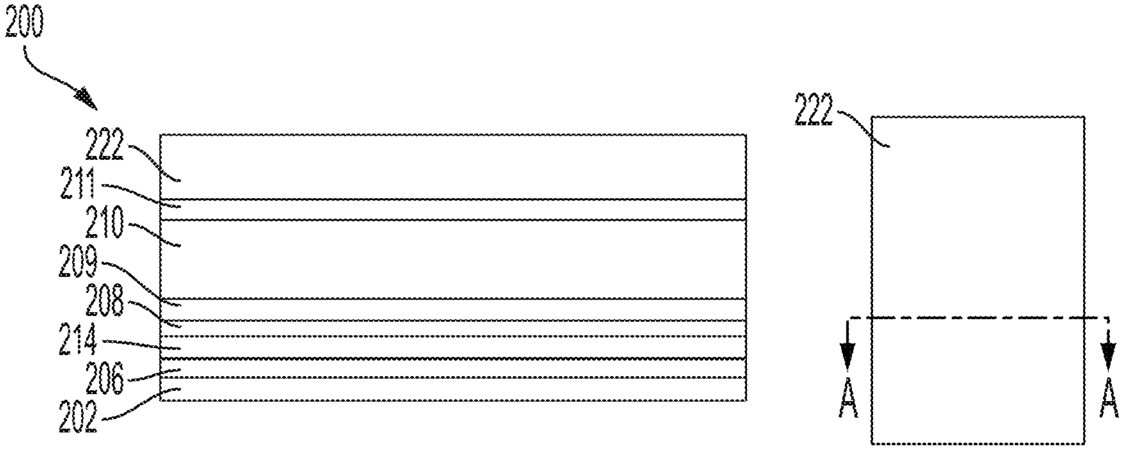
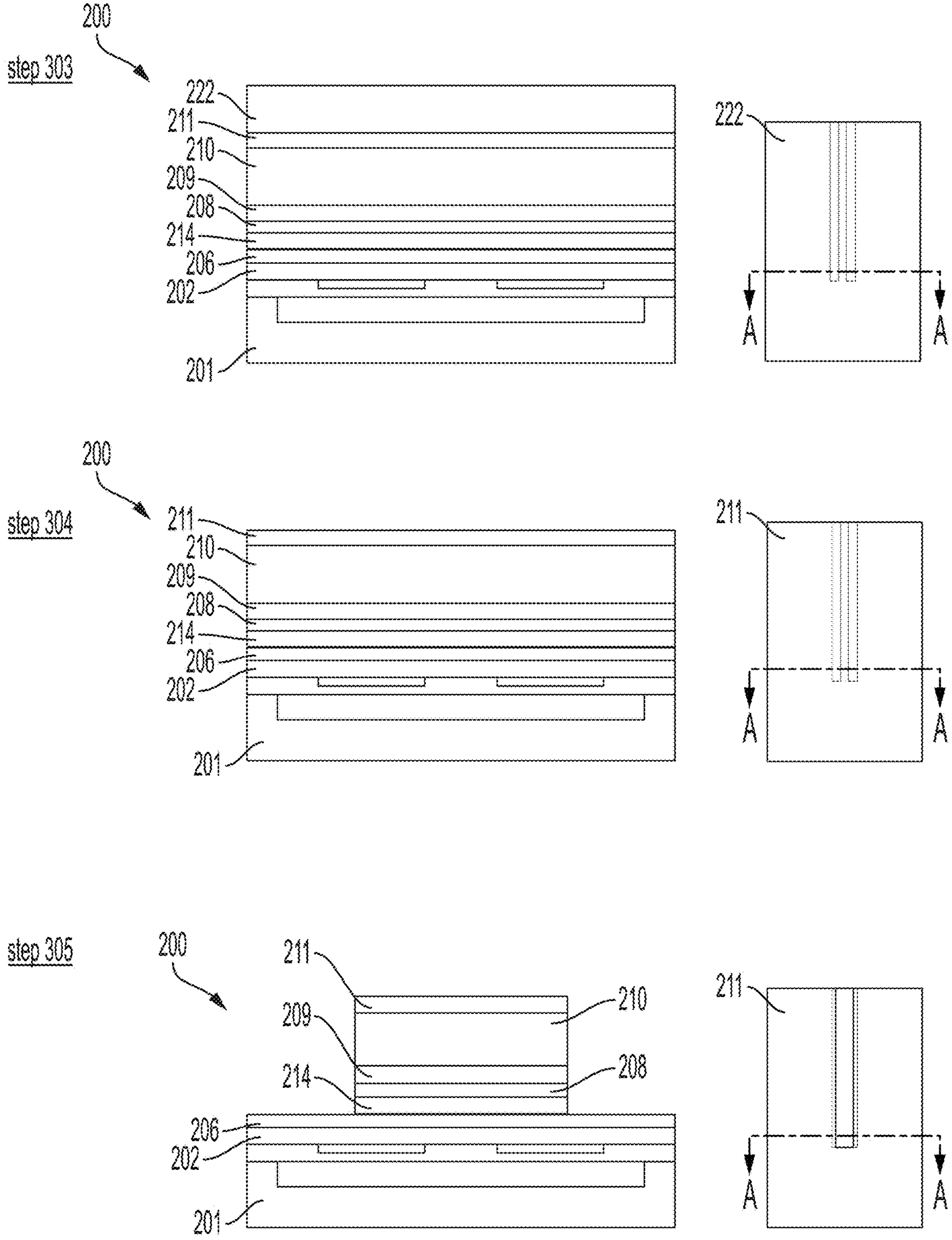


FIG. 25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step 304
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214
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A
step 305
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206
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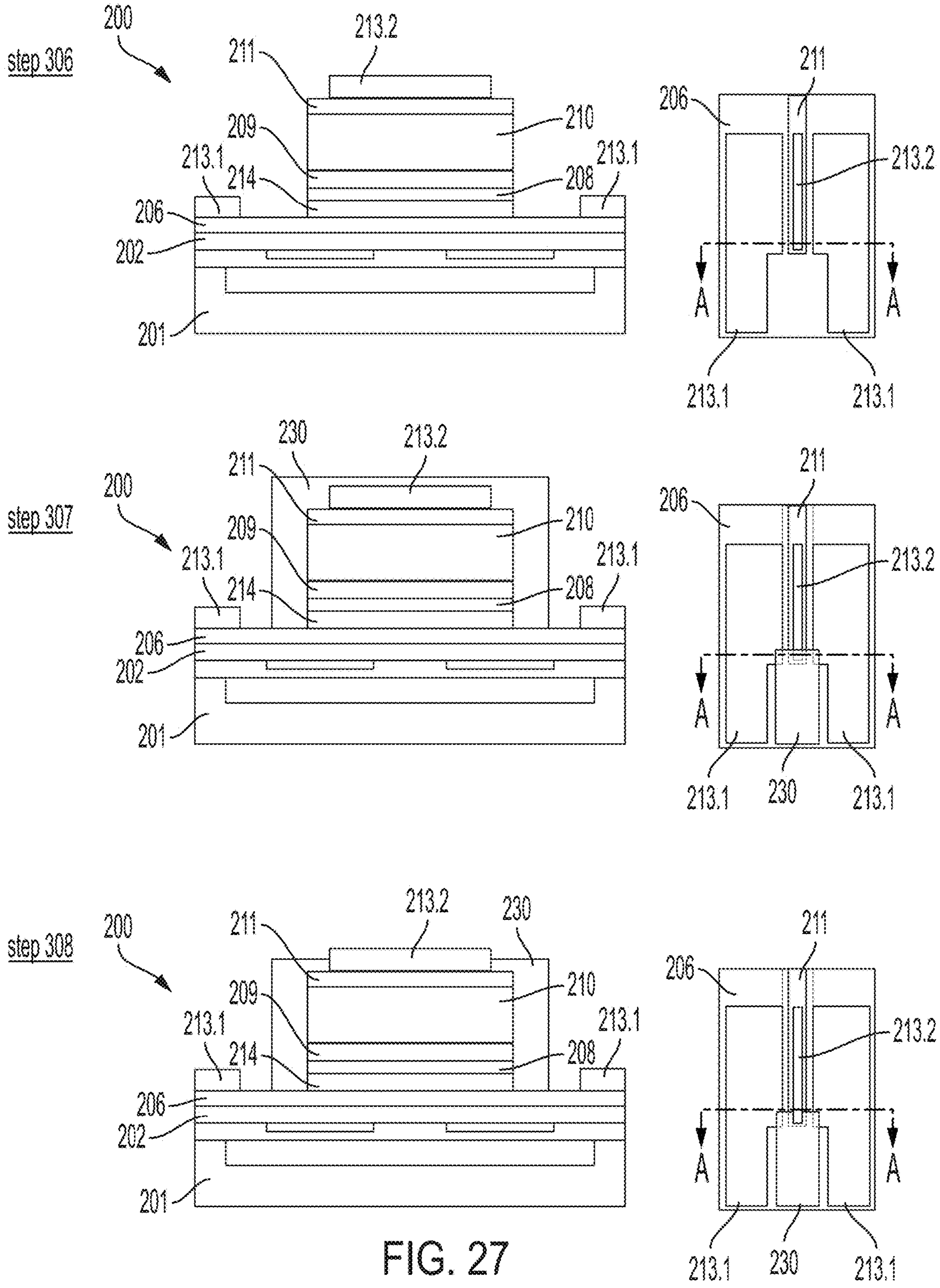
201
211
A
A

FIG. 26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step 307
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213.2
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A
213.1
230
213.1
step 308
200
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211
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209
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213.2
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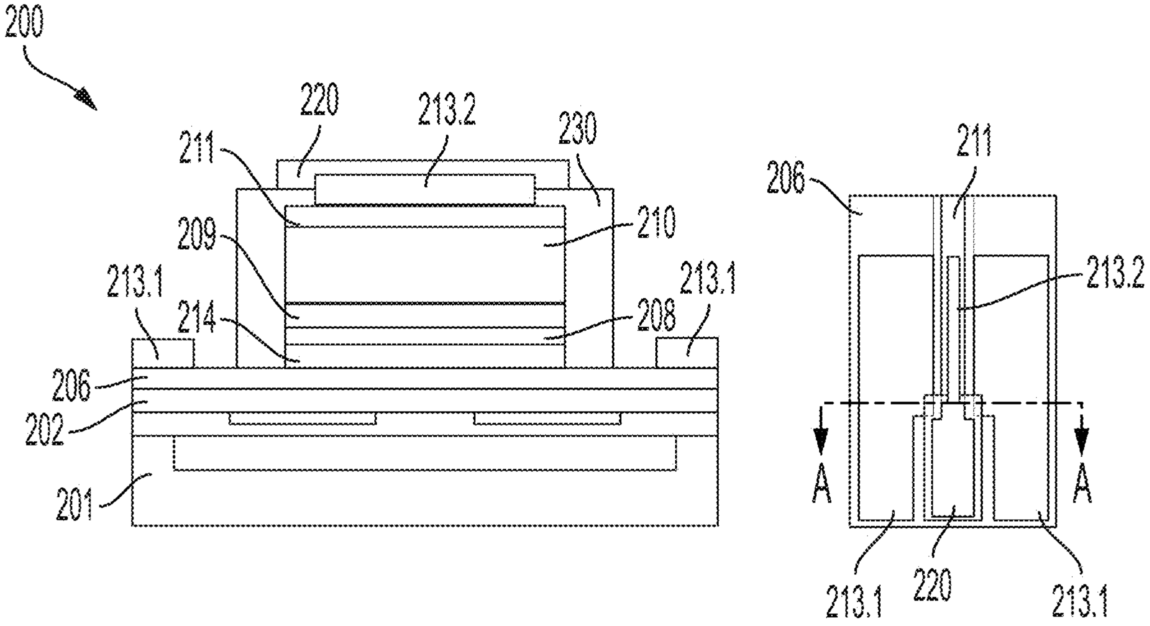
213.1
230
213.1

FIG. 27

step 309



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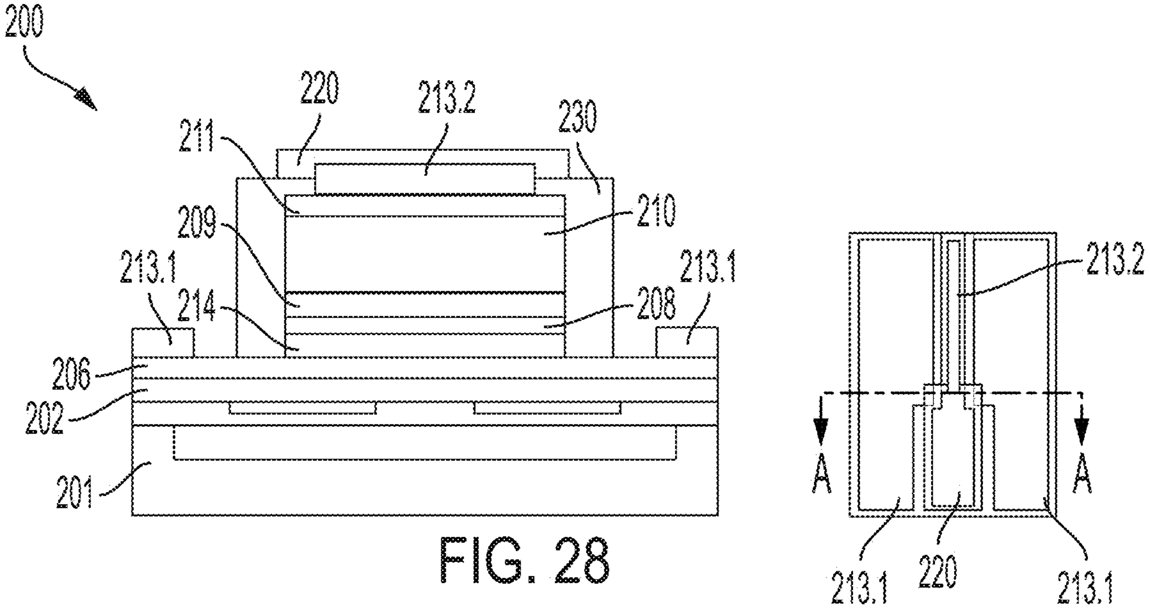
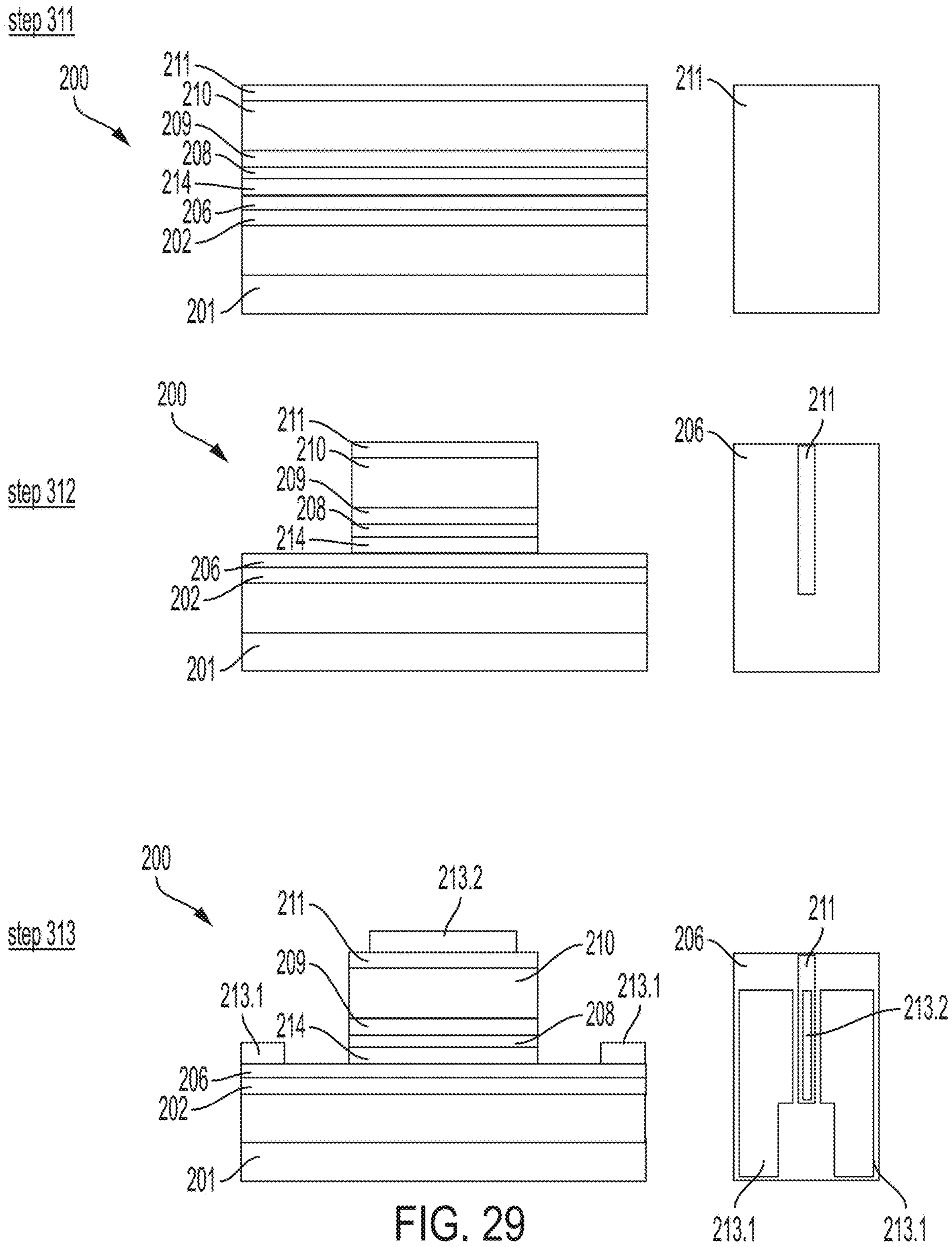


FIG. 28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202
201
206
211
200
step 313
213.2
211
210
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213.1
213.1
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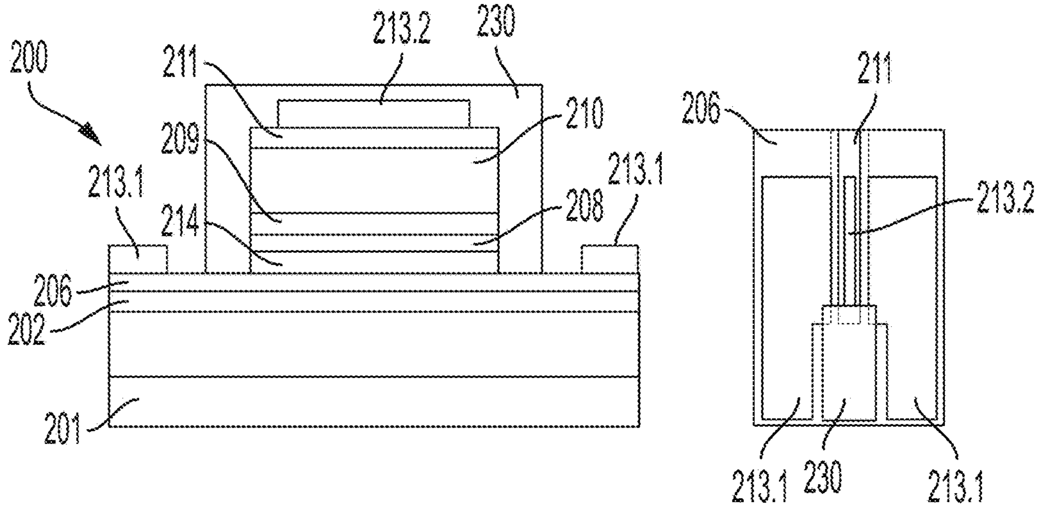
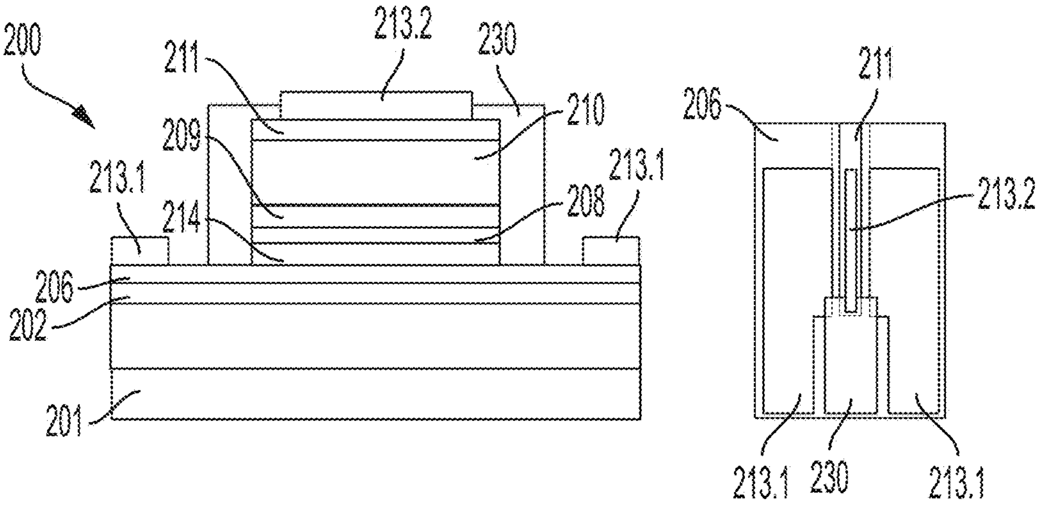
206
202
201
206
211
213.2
213.1
213.1

FIG. 29

step 314



step 315



step 316

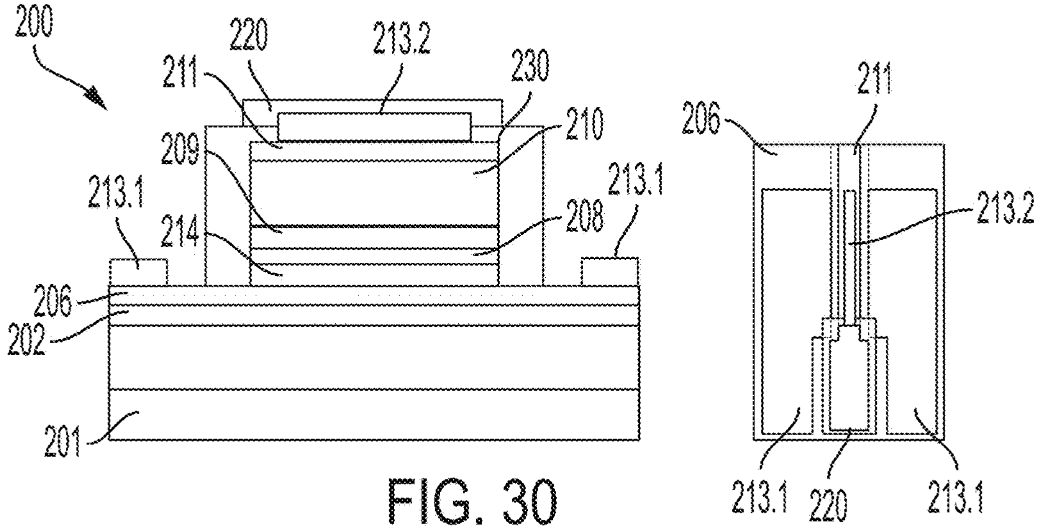


FIG. 30

step 317

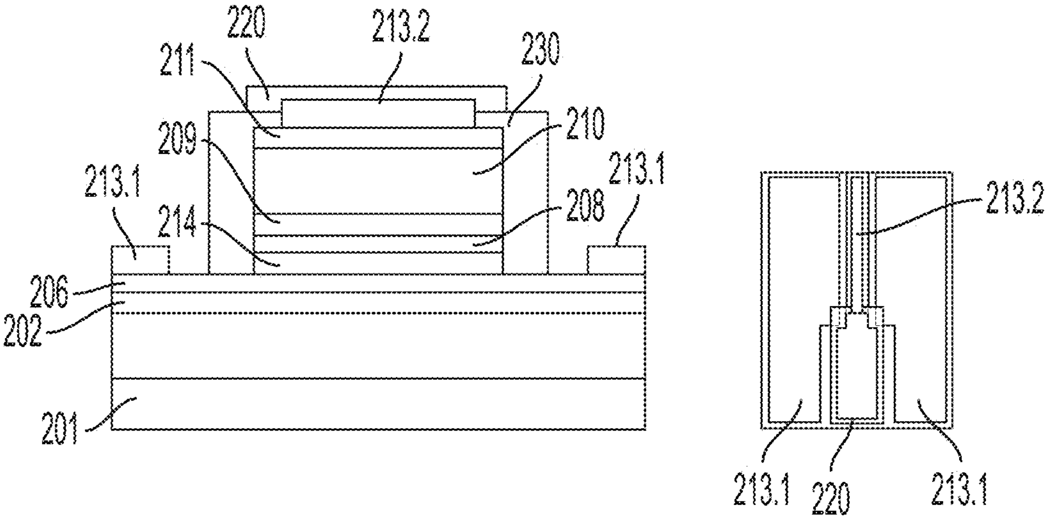


FIG. 31

QUANTUM WAVEGUIDE INFRARED PHOTODETECTOR

CROSS REFERENCE TO RELATED APPLICATIONS

The application claims priority to U.S. Provisional Patent Application Ser. No. 62/877,932 filed Jul. 24, 2019, the disclosure of which is incorporated herein by reference in its entirety.

STATEMENT REGARDING FEDERALLY SPONSORED RESEARCH

This invention was made with United States Government support from the National Institute of Standards and Technology (NIST), an agency of the United States Department of Commerce. The Government has certain rights in the invention. Licensing inquiries may be directed to the Technology Partnerships Office, NIST, Gaithersburg, Md., 20899; voice (301) 975-2573; email tpo@nist.gov; reference NIST Docket Number 19-042US1.

BRIEF DESCRIPTION

Disclosed is a quantum waveguide infrared photodetector for detecting infrared photons by intersubband transitions in a semiconductor of a photon absorption layer, the quantum waveguide infrared photodetector comprising: the photon absorption layer that receives infrared photons propagating longitudinally along a longitudinal length of the photon absorption layer, converts the infrared photons into electrons, and communicates the electrons to a conductor layer; a barrier layer on which the photon absorption layer is disposed; a semiconductor contact layer on which the barrier layer is disposed; a semiconductor member on which the semiconductor contact layer is disposed; a substrate on which the semiconductor member is disposed; a barrier layer disposed on the photon absorption layer; a buffer layer disposed on the barrier layer; a semiconductor contact layer disposed on the buffer layer; a first conductor layer disposed on the semiconductor contact layer and that receives a first electrical potential; and a second conductor layer disposed on the semiconductor contact layer and that receives a second electrical potential, wherein electrons produced by the photon absorption layer in response to receipt of the infrared photons are communicated from the photon absorption layer: to the first conductor layer when the first electrical potential is more positive than the second electrical potential, and to the second conductor layer when the second electrical potential is more positive than the first electrical potential, an electrical current produced by the electrons is proportional to an amount of absorption of the infrared photons in the photon absorption layer.

Disclosed is a process for detecting infrared photons by intersubband transitions in a semiconductor of a photon absorption layer with the quantum waveguide infrared photodetector of claim **1**, the process comprising: receiving, by the photon absorption layer, the infrared photons; propagating longitudinally the infrared photons along the longitudinal length of the photon absorption layer; converting, by the photon absorption layer, the infrared photons into electrons by intersubband transitions in the semiconductor of the photon absorption layer; biasing the first conductor layer with the first electrical potential; biasing the second conductor layer with the second electrical potential; communicating the electrons from the photon absorption layer to the first conductor layer when the first electrical potential is more positive than the second electrical potential; and communicating the electrons from the photon absorption layer to the second conductor layer when the second electrical potential is more positive than the first electrical potential to detect the infrared photons, wherein an electrical current produced by the electrons is proportional to the amount of absorption of the infrared photons in the photon absorption layer.

BRIEF DESCRIPTION OF THE DRAWINGS

The following description should not be considered limiting in any way. With reference to the accompanying drawings, like elements are numbered alike.

FIG. **1** shows a plan view of an embodiment of quantum waveguide infrared photodetector **200**;

FIG. **2** shows a cross-section along line A-A in panel A and a cross-section along line B-B of an embodiment of quantum waveguide infrared photodetector **200** show in FIG. **1**;

FIG. **3** shows a cross-section along line A-A in panel A and a cross-section along line B-B of an embodiment of quantum waveguide infrared photodetector **200** show in FIG. **1**;

FIG. **4** shows a cross-section along line A-A in panel A and a cross-section along line B-B of an embodiment of quantum waveguide infrared photodetector **200** show in FIG. **1**;

FIG. **5** shows a cross-section along line A-A in panel A and a cross-section along line B-B of an embodiment of quantum waveguide infrared photodetector **200** show in FIG. **1**;

FIG. **6** shows a plan view of an embodiment of quantum waveguide infrared photodetector **200**;

FIG. **7** shows an embodiment of quantum waveguide infrared photodetector **200** with electrons received by conductor layer **213.1** in panel A due to electrical biasing with electrical bias supply **225** and electrons received by conductor layer **213.2** in panel B due to electrical biasing with electrical bias supply **225**;

FIG. **8** shows a map of a magnitude of an electromagnetic field of a transverse electromagnetic mode for infrared photons propagating longitudinally in photon absorption layer **208** and layers proximate to photon absorption layer **208** for a transverse cross-section of an embodiment of quantum waveguide infrared photodetector **200**;

FIG. **9** shows steps involved in making quantum waveguide infrared photodetector **200** show in FIG. **2**;

FIG. **10** shows steps involved in making quantum waveguide infrared photodetector **200** show in FIG. **2**;

FIG. **11** shows steps involved in making quantum waveguide infrared photodetector **200** show in FIG. **2**;

FIG. **12** shows steps involved in making quantum waveguide infrared photodetector **200** show in FIG. **2**;

FIG. **13** shows steps involved in making quantum waveguide infrared photodetector **200** show in FIG. **2**;

FIG. **14** shows steps involved in making quantum waveguide infrared photodetector **200** show in FIG. **2**;

FIG. **15** shows steps involved in making quantum waveguide infrared photodetector **200** show in FIG. **2**;

FIG. **16** shows steps involved in making quantum waveguide infrared photodetector **200** show in FIG. **2**;

FIG. **17** shows steps involved in making quantum waveguide infrared photodetector **200** show in FIG. **2**;

FIG. **18** shows steps involved in making quantum waveguide infrared photodetector **200** show in FIG. **2**;

FIG. **19** shows steps involved in making quantum waveguide infrared photodetector **200** show in FIG. **3**;

FIG. **20** shows steps involved in making quantum waveguide infrared photodetector **200** show in FIG. **3**;

FIG. **21** shows steps involved in making quantum waveguide infrared photodetector **200** show in FIG. **3**;

FIG. **22** shows steps involved in making quantum waveguide infrared photodetector **200** show in FIG. **3**;

FIG. **23** shows steps involved in making quantum waveguide infrared photodetector **200** show in FIG. **4**;

FIG. **24** shows steps involved in making quantum waveguide infrared photodetector **200** show in FIG. **4**;

FIG. **25** shows steps involved in making quantum waveguide infrared photodetector **200** show in FIG. **4**;

FIG. **26** shows steps involved in making quantum waveguide infrared photodetector **200** show in FIG. **4**;

FIG. **27** shows steps involved in making quantum waveguide infrared photodetector **200** show in FIG. **4**;

FIG. **28** shows steps involved in making quantum waveguide infrared photodetector **200** show in FIG. **4**;

FIG. **29** shows steps involved in making quantum waveguide infrared photodetector **200** show in FIG. **5**;

FIG. **30** shows steps involved in making quantum waveguide infrared photodetector **200** show in FIG. **5**; and

FIG. **31** shows steps involved in making quantum waveguide infrared photodetector **200** show in FIG. **5**.

DETAILED DESCRIPTION

A detailed description of one or more embodiments is presented herein by way of exemplification and not limitation.

It has been discovered that quantum waveguide infrared photodetector **200** provides a greater signal-to-noise ratio compared with conventional infrared detectors. Beneficially, quantum waveguide infrared photodetector **200** receives infrared photons injected in absorbing regions of quantum waveguide infrared photodetector **200** in a plane of material layers of quantum waveguide infrared photodetector **200** instead of surface normal to the material layers of quantum waveguide infrared photodetector **200** as conventional detectors do. Unexpectedly, quantum waveguide infrared photodetector **200** provides room-temperature detection of infrared light with high sensitivity and high speed and can be a detector for infrared absorption spectroscopy, optical coherence tomography, light detection and ranging, communications, and the like.

Quantum waveguide infrared photodetector **200** detects infrared photons **224** by intersubband transitions in a semiconductor of photon absorption layer **208**. In an embodiment, with reference to FIG. **1**, FIG. **2**, FIG. **3**, FIG. **4**, FIG. **5**, FIG. **6**, and FIG. **7**, quantum waveguide infrared photodetector **200** includes: photon absorption layer **208** that receives infrared photons **224** propagating longitudinally along a longitudinal length (indicated in FIG. **1** as being in a direction along X-axis) of photon absorption layer **208**, converts infrared photons **224** into electrons **221**, and communicates electrons **221** to conductor layer **213**; barrier layer **214** on which photon absorption layer **208** is disposed; semiconductor contact layer **206** on which barrier layer **214** is disposed; semiconductor member **202** on which semiconductor contact layer **206** is disposed; a substrate **201** on which semiconductor member **202** is disposed; a barrier layer **209** disposed on photon absorption layer **208**; a buffer layer **210** disposed on barrier layer **209**; a semiconductor contact layer **211** disposed on buffer layer **210**; a first conductor layer **213.1** disposed on semiconductor contact layer **206** and that receives a first electrical potential; and a second conductor layer **213.2** disposed on semiconductor contact layer **211** and that receives a second electrical potential, wherein electrons **221** produced by photon absorption layer **208** in response to receipt of infrared photons **224** are communicated from photon absorption layer **208**: to first conductor layer **213.1** (as electrons **221.1**) when the first electrical potential is more positive than the second electrical potential, and to second conductor layer **213.2** (as electrons **221.2**) when the second electrical potential is more positive than the first electrical potential, an electrical current produced by electrons **221** is proportional to an amount of absorption of infrared photons **224** in photon absorption layer **208**.

In an embodiment, quantum waveguide infrared photodetector **200** further includes mode confinement layer **203** interposed between substrate **201** and semiconductor member **202** and bounded by surfaces of substrate **201** and semiconductor member **202**.

In an embodiment, quantum waveguide infrared photodetector **200** further includes core layer **215** interposed between substrate **201** and semiconductor member **202**.

In an embodiment, quantum waveguide infrared photodetector **200** further includes bottom cladding **216** interposed between core layer **215** and substrate **201**.

In an embodiment, quantum waveguide infrared photodetector **200** further includes mode confinement layer **203** disposed in core layer **215** and interposed between bottom cladding **216** and semiconductor member **202**.

In an embodiment, quantum waveguide infrared photodetector **200** further includes mode confinement layer **203** is bounded by surfaces of bottom cladding **216**, core layer **215**, and semiconductor member **202**.

In an embodiment, quantum waveguide infrared photodetector **200** further includes second mode confinement layer **203.2** disposed in semiconductor member **202**, interposed between semiconductor member **202** and semiconductor contact layer **206**, and bounded by surfaces of semiconductor member **202** and semiconductor contact layer **206**.

In an embodiment, quantum waveguide infrared photodetector **200** further includes first electrical contact pad **220.1** disposed on substrate **201** and first conductor layer **213.1** and in electrical communication with first conductor layer **213.1**, such that first electrical contact pad **220.1** receives the first electrical potential for electrically biasing first conductor layer **213.1**.

In an embodiment, quantum waveguide infrared photodetector **200** further includes second electrical contact pad **220.2** disposed on substrate **201** and second conductor layer **213.2** and in electrical communication with second conductor layer **213.2**, such that second electrical contact pad **220.2** receives the second electrical potential for electrically biasing second conductor layer **213.2**.

In an embodiment, with reference to FIG. **16**, quantum waveguide infrared photodetector **200** further includes electrical insulator **230** disposed on semiconductor contact layer **211** and semiconductor contact layer **206** and that electrically insulates first conductor layer **213.1** from second conductor layer **213.2**.

In an embodiment, with reference to FIG. **7**, quantum waveguide infrared photodetector **200** further includes electrical bias supply **225** in electrical communication with first conductor layer **213.1** and second conductor layer **213.2**, wherein electrical bias supply **225** provides the first electrical potential to first conductor layer **213.1** and the second electrical potential to second conductor layer **213.2**. Quantum waveguide infrared photodetector **200** can include current meter **226** in electrical communication with first conductor layer **213.1** and electrical bias supply **225**, wherein current meter **226** receives detector signal **227** and determines the amount of electrical current from detector signal **227**.

Components of quantum waveguide infrared photodetector **200** can be made from and include various materials. Substrate **201** provides mechanical structure for other elements of quantum waveguide infrared photodetector **200** and provides electrical insulation for quantum waveguide infrared photodetector **200**. Substrate **201** can include silicon, quartz, gallium arsenide, and the like. A thickness of substrate **201** can be from 1 nm to 10 mm, specifically from 1 μm to 2 mm, and more specifically from 50 μm to 800 μm. It is contemplated that a diameter of substrate **201** can be from 1 μm to 1 m, specifically from 1 mm to 500 mm, and more specifically from 50 mm to 300 mm. An electrical resistivity of substrate **201** can be from 10^{-10} Ωm to 10^{16} Ωm, specifically from 10^{-8} Ωm to 10^{3} Ωm, and more specifically from 10^{-5} Ωm to 500 Ωm. Further, if substrate **201** is crystalline, a crystal axis orientation of substrate **201** can be in any direction. In an embodiment, substrate **201** is silicon.

Semiconductor member **202** optimizes the guided optical mode overlap with photon absorption layer **208**. Semiconductor member **202** can include silicon, quartz, gallium arsenide, aluminum gallium arsenide, and the like. An elemental composition of this layer can include gallium in an amount from 1 atomic percent (at. %) to 100 at. %, specifically from 25 at. % to 75 at. %, and more specifically from 40 at. % to 60 at. %, based on a total of all atoms in this layer; and arsenic in an amount from 1 atomic percent (at. %) to 100 at. %, specifically from 25 at. % to 75 at. %, and more specifically from 40 at. % to 60 at. %, based on a total of all atoms in this layer. A thickness of semiconductor member **202** can be from 1 nm to 1 cm, specifically from 5 nm to 10 μm, and more specifically from 100 nm to 5 μm. An electrical resistivity of semiconductor member **202** can be from 10^{-10} Ωm to 10^{16} Ωm, specifically from 10^{-8} Ωm to 10^{3} Ωm, and more specifically from 10^{-5} Ωm to 500 Ωm. In an embodiment, semiconductor member **202** is gallium arsenide. In some embodiments, mode confinement layer **203** is disposed in semiconductor member **202**, wherein semiconductor air gap surface **218** and semiconductor air gap surface **219** are surfaces that provide a boundary for mode confinement layer **203** that can be an air gap.

Mode confinement layer **203** provides a lower refractive index than the waveguide core and has low loss so the optical mode is efficiently guided through photon absorption layer **208** without radiating infrared photons **224** toward substrate **201**. Mode confinement layer **203** can include an air gap, aluminum gallium arsenide, and the like. An elemental composition of this layer can include gallium in an amount from 0 atomic percent (at. %) to 100 at. %, specifically from 5 at. % to 95 at. %, and more specifically from 10 at. % to 80 at. %, based on a total of gallium and aluminum atoms in this layer; aluminum in an amount from 0 atomic percent (at. %) to 100 at. %, specifically from 5 at. % to 95 at. %, and more specifically from 20 at. % to 90 at. %, based on a total of gallium and aluminum atoms in this layer; and arsenic in an amount from 1 atomic percent (at. %) to 100 at. %, specifically from 25 at. % to 75 at. %, and more specifically from 40 at. % to 60 at. %, based on a total of all atoms in this layer. A thickness of mode confinement layer **203** can be from 1 nm to 1 cm, specifically from 100 nm to 1 mm, and more specifically from 200 nm to 10 μm. It is contemplated that a width of mode confinement layer **203** can be from 1 nm to 1 cm, specifically from 500 nm to 1 mm, and more specifically from 1 μm to 50 μm. An electrical resistivity of mode confinement layer **203** can be from 10^{-10} Ωm to 10^{16} Ωm, specifically from 10^{-8} Ωm to 10^{3} Ωm, and more specifically from 10^{-5} Ωm to 500 Ωm. In an embodiment, mode confinement layer **203** is an air gap. Substrate gap surface **204** and semiconductor gap surface **205** are surfaces that provide a boundary for mode confinement layer **203**.

Semiconductor contact layer **206** extracts or injects electrons **221** to or from photon absorption layer **208** and barrier layer **214**; to provide low resistance to conductor layer **213**. Semiconductor contact layer **206** can include silicon, gallium arsenide, aluminum gallium arsenide, and the like. An elemental composition of this layer can include gallium in an amount from 0 atomic percent (at. %) to 100 at. %, specifically from 5 at. % to 95 at. %, and more specifically from 10 at. % to 80 at. %, based on a total of gallium and aluminum atoms in this layer; aluminum in an amount from 0 atomic percent (at. %) to 100 at. %, specifically from 5 at. % to 95 at. %, and more specifically from 20 at. % to 90 at. %, based on a total of gallium and aluminum atoms in this layer; and arsenic in an amount from 1 atomic percent (at. %) to 100 at. %, specifically from 25 at. % to 75 at. %, and more specifically from 40 at. % to 60 at. %, based on a total of all atoms in this layer. A thickness of semiconductor contact layer **206** can be from 1 nm to 1 cm, specifically from 10 nm to 1 mm, and more specifically from 100 nm to 1 μm. It is contemplated that a width of semiconductor contact layer **206** can be from 1 nm to 1 cm, specifically from 100 nm to 1 mm, and more specifically from 1 μm to 10 μm. An electrical resistivity of semiconductor contact layer **206** can be from 10^{-10} Ωm to 10^{16} Ωm, specifically from 10^{-8} Ωm to 10^{3} Ωm, and more specifically from 10^{-5} Ωm to 500 Ωm. In an embodiment, semiconductor contact layer **206** is gallium arsenide. Semiconductor contact surface **207** is a surface of semiconductor contact layer **206** on which barrier layer **214** and conductor layer **213** are formed.

Photon absorption layer **208** has a chosen composition and thickness to selectively absorb infrared photons **224** incident to or propagating through quantum waveguide infrared photodetector **200**. Photon absorption layer **208** can include a quantum well, quantum dot, or quantum dash, wherein exemplary quantum wells include gallium, arsenic, indium, aluminum and the like; exemplary quantum dots include gallium, arsenic, indium, aluminum, and the like; and exemplary quantum dashes include gallium, arsenic, indium, aluminum, and the like. An elemental composition of this layer can include gallium in an amount from 0 atomic percent (at. %) to 100 at. %, specifically from 5 at. % to 95 at. %, and more specifically from 10 at. % to 80 at. %, based on a total of gallium and indium atoms in this layer; indium in an amount from 0 atomic percent (at. %) to 100 at. %, specifically from 5 at. % to 95 at. %, and more specifically from 20 at. % to 90 at. %, based on a total of gallium and indium atoms in this layer; and arsenic in an amount from 1 atomic percent (at. %) to 100 at. %, specifically from 25 at. % to 75 at. %, and more specifically from 40 at. % to 60 at. %, based on a total of all atoms in this layer. A thickness of photon absorption layer **208** can be from 100 μm to 1 cm, specifically from 1 nm to 100 nm, and more specifically from 2 nm to 10 nm. It is contemplated that a width of photon absorption layer **208** can be from 1 nm to 1 cm, specifically from 100 nm to 10 mm, and more specifically from 1 μm to 100 μm. An electrical resistivity of photon absorption layer **208** can be from 10^{-10} Ωm to 10^{16} Ωm, specifically from 10^{-8} Ωm to 10^{3} Ωm, and more specifically from 10^{-5} Ωm to 500 Ωm. Further, photon absorption layer **208** can absorb wavelengths from 100 nm to 100 Ωm, specifically from 1 μm to 20 μm, more specifically from 2 μm to 15 μm. In an embodiment, photon absorption layer **208** is a quantum well that includes indium gallium arsenide.

In an embodiment, quantum waveguide infrared photodetector **200** includes a single infrared absorbing layer **208**, rather than a plurality of infrared absorbing layers (e.g., ~40 layers) as in conventional devices. In some embodiments, quantum waveguide infrared photodetector **200** includes a plurality of absorption layers, wherein each photon absorption layer **208** has a different quantum well thickness to increase optical bandwidth of quantum waveguide infrared photodetector **200**.

Barrier layer **209** supports selected electronic energy states bound or quasi-bound by photon absorption layer **208** to correspond to an energy of infrared photons **224**. Barrier layer **209** can include aluminum gallium arsenide and the like. An elemental composition of this layer can include gallium in an amount from 0 atomic percent (at. %) to 100 at. %, specifically from 5 at. % to 95 at. %, and more specifically from 10 at. % to 80 at. %, based on a total of gallium and aluminum atoms in this layer; aluminum in an amount from 0 atomic percent (at. %) to 100 at. %, specifically from 5 at. % to 95 at. %, and more specifically from 20 at. % to 90 at. %, based on a total of gallium and aluminum atoms in this layer; and arsenic in an amount from 1 atomic percent (at. %) to 100 at. %, specifically from 25 at. % to 75 at. %, and more specifically from 40 at. % to 60 at. %, based on a total of all atoms in this layer. A thickness of barrier layer **209** can be from 100 μm to 1 cm, specifically from 1 nm to 1 μm, and more specifically from 2 nm to 500 nm. It is contemplated that a width of barrier layer **209** can be from 1 nm to 1 cm, specifically from 100 nm to 10 mm, and more specifically from 1 μm to 100 μm. An electrical resistivity of barrier layer **209** can be from 10^{-10} Ωm to 10^{16} Ωm, specifically from 10^{-8} Ωm to 10^{3} Ωm, and more specifically from 10^{-5} Ωm to 500 Ωm. In an embodiment, barrier layer **209** is aluminum gallium arsenide.

Buffer layer **210** provides a lower refractive index region than the waveguide core and has low loss so the optical mode of infrared photons **224** is efficiently guided without radiating toward semiconductor contact layer **211** or second conductor layer **213.2**. Buffer layer **210** can include aluminum gallium arsenide and the like. An elemental composition of this layer can include gallium in an amount from 0 atomic percent (at. %) to 100 at. %, specifically from 5 at. % to 95 at. %, and more specifically from 10 at. % to 80 at. %, based on a total of gallium and aluminum atoms in this layer; aluminum in an amount from 0 atomic percent (at. %) to 100 at. %, specifically from 5 at. % to 95 at. %, and more specifically from 20 at. % to 90 at. %, based on a total of gallium and aluminum atoms in this layer; and arsenic in an amount from 1 atomic percent (at. %) to 100 at. %, specifically from 25 at. % to 75 at. %, and more specifically from 40 at. % to 60 at. %, based on a total of all atoms in this layer. A thickness of buffer layer **210** can be from 100 μm to 1 cm, specifically from 1 nm to 10 μm, and more specifically from 100 nm to 5 μm. It is contemplated that a width of buffer layer **210** can be from 1 nm to 1 cm, specifically from 100 nm to 10 mm, and more specifically from 1 μm to 100 μm. An electrical resistivity of buffer layer **210** can be from 10^{-10} Ωm to 10^{16} Ωm, specifically from 10^{-8} Ωm to 10^{3} Ωm, and more specifically from 10^{-5} Ωm to 500 Ωm. In an embodiment, buffer layer **210** is aluminum gallium arsenide.

Semiconductor contact layer **211** extracts or injects electrons **221** to or from photon absorption layer **208** and barrier layer **209** to provide low resistance to second conductor layer **213.2**. Semiconductor contact layer **211** can include aluminum gallium arsenide and the like. An elemental composition of this layer can include gallium in an amount from 0 atomic percent (at. %) to 100 at. %, specifically from 5 at. % to 95 at. %, and more specifically from 10 at. % to 80 at. %, based on a total of gallium and aluminum atoms in this layer; aluminum in an amount from 0 atomic percent (at. %) to 100 at. %, specifically from 5 at. % to 95 at. %, and more specifically from 20 at. % to 90 at. %, based on a total of gallium and aluminum atoms in this layer; and arsenic in an amount from 1 atomic percent (at. %) to 100 at. %, specifically from 25 at. % to 75 at. %, and more specifically from 40 at. % to 60 at. %, based on a total of all atoms in this layer. A thickness of semiconductor contact layer **211** can be from 1 nm to 1 cm, specifically from 1 nm to 10 μm, and more specifically from 10 nm to 1 μm. It is contemplated that a width of semiconductor contact layer **211** can be from 1 nm to 1 cm, specifically from 100 nm to 10 mm, and more specifically from 1 μm to 100 μm. An electrical resistivity of semiconductor contact layer **211** can be from 10^{-10} Ωm to 10^{16} Ωm, specifically from 10^{-8} μm to 10^{3} Ωm, and more specifically from 10^{-5} Ωm to 500 Ωm. In an embodiment, semiconductor contact layer **211** is gallium arsenide. Top contact surface **212** is a surface of semiconductor contact layer **211** on which second conductor layer **213.2** is formed.

Conductor layer **213** is electrically conductive and provides an electrical interface to quantum waveguide infrared photodetector **200** for communicating detector signal **227** from quantum waveguide infrared photodetector **200** and for subjecting layers of quantum waveguide infrared photodetector **200** to a potential difference. Conductor layer **213** can include a metal (e.g., gold, nickel, germanium, and the like) or other electrically conductive material (e.g., indium tin oxide and the like). A thickness of conductor layer **213** can be from 1 nm to 1 cm, specifically from 10 nm to 1 mm, and more specifically from 100 nm to 2 μm. It is contemplated that a width of conductor layer **213** can be from 1 nm to 1 cm, specifically from 100 nm to 10 mm, and more specifically from 1 μm to 100 μm. An electrical resistivity of conductor layer **213** can be from 10^{-10} Ωm to 10^{16} t m, specifically from 10^{-8} Ωm to 10^{3} Ωm, and more specifically from 10^{-5} Ωm to 500 Ωm. In an embodiment, conductor layer **213** is nickel, gold-germanium eutectic alloy, nickel, and gold. Conductor layer **213** can be made of a plurality of stacked layers that, e.g., include an order of layers stacked as follows: nickel, a gold/germanium alloy, nickel, and gold. Other combinations of metals can be used for conductor layer **213**. Stacking layers in conductor layer **213** can be referred to as a semiconductor contact metal stack that differs depending on a type of dopant and semiconductor composition of such layers.

Barrier layer **214** supports selected electronic energy states bound by photon absorption layer **208** to correspond to an energy of infrared photons **224**. Barrier layer **214** can include aluminum gallium arsenide and the like. An elemental composition of this layer can include gallium in an amount from 0 atomic percent (at. %) to 100 at. %, specifically from 5 at. % to 95 at. %, and more specifically from 10 at. % to 80 at. %, based on a total of gallium and aluminum atoms in this layer; aluminum in an amount from 0 atomic percent (at. %) to 100 at. %, specifically from 5 at. % to 95 at. %, and more specifically from 20 at. % to 90 at. %, based on a total of gallium and aluminum atoms in this layer; and arsenic in an amount from 1 atomic percent (at.

%) to 100 at. %, specifically from 25 at. % to 75 at. %, and more specifically from 40 at. % to 60 at. %, based on a total of all atoms in this layer. A thickness of barrier layer **214** can be from 100 pm to 1 cm, specifically from 1 nm to 1 μm, and more specifically from 2 nm to 500 nm. It is contemplated that a width of barrier layer **214** can be from 1 nm to 1 cm, specifically from 100 nm to 10 mm, and more specifically from 1 μm to 100 μm. An electrical resistivity of barrier layer **214** can be from 10^{-10} Ωm to 10^{16} Ωm, specifically from 10^{-8} Ωm to 10^{3} Ωm, and more specifically from 10^{-5} Ωm to 500 Ωm. In an embodiment, barrier layer **214** is aluminum gallium arsenide.

Core layer **215** provides optical confinement of quantum waveguide infrared photodetector **200** and selectively optimizes optical overlap with photon absorption layer **208**. Core layer **215** can include silicon, quartz, gallium arsenide, and the like. A thickness of core layer **215** can be from 1 nm to 1 cm, specifically from 100 nm to 1 mm, and more specifically from 200 nm to 10 μm. It is contemplated that a width of core layer **215** can be from 1 nm to 1 cm, specifically from 100 nm to 10 mm, and more specifically from 1 μm to 100 μm. An electrical resistivity of core layer **215** can be from 10^{-10} Ωm to 10^{16} Ωm, specifically from 10^{-8} Ωm to 10^{3} Ωm, and more specifically from 10^{-5} m to 500 Ωm. In an embodiment, core layer **215** is silicon. In some embodiments, mode confinement layer **203** is disposed in core layer **215**, wherein substrate gap surface **204**, semiconductor gap surface **205**, and cladding air gap surface **217** are surfaces that provide a boundary for mode confinement layer **203** that can be an air gap.

Bottom cladding **216** has a lower refractive index than core layer **215** and low loss so the optical mode is efficiently guided through photon absorption layer **208** without radiating toward substrate **201**. Bottom cladding **216** can include an oxidized material that forms substrate **201**, e.g., silicon dioxide and the like. A thickness of bottom cladding **216** can be from 1 nm to 1 cm, specifically from 100 nm to 1 mm, and more specifically from 1 μm to 20 μm. It is contemplated that width of bottom cladding **216** can be from 1 nm to 1 cm, specifically from 500 nm to 1 mm, and more specifically from 1 μm to 50 μm. An electrical resistivity of bottom cladding **216** can be from 10^{-10} Ωm to 10^{16} Ωm, specifically from 10^{-8} Ωm to 10^{3} Ωm, and more specifically from 10^{-5} Ωm to 500 Ωm. In an embodiment, bottom cladding **216** is silicon dioxide.

Electrical contact pad **220** is electrically conductive and provides an electrical interface to quantum waveguide infrared photodetector **200** for communicating detector signal **227** from quantum waveguide infrared photodetector **200** and for subjecting layers of quantum waveguide infrared photodetector **200** to a potential difference via conductor layer **213**. Electrical contact pad **220** can include a stack of metal layers (e.g., gold, nickel, germanium, and the like) or other electrically conductive material (e.g., indium tin oxide and the like) formatted as a semiconductor contact metal stack. A thickness of electrical contact pad **220** can be from 1 nm to 1 cm, specifically from 10 nm to 1 mm, and more specifically from 100 nm to 2 μm. It is contemplated that a width of electrical contact pad **220** can be from 1 nm to 1 cm, specifically from 100 nm to 10 mm, and more specifically from 1 μm to 100 μm. An electrical resistivity of electrical contact pad **220** can be from 10^{-10} Ωm to 10^{16} Ωm, specifically from 10^{-8} Ωm to 10^{3} Ωm, and more specifically from 10^{-5} m to 500 Ωm. In an embodiment, electrical contact pad **220** is titanium and gold.

In accordance with the foregoing description of quantum waveguide infrared photodetector **200**, it should be appreciated that quantum waveguide infrared photodetector **200** includes a composite structure of a plurality of components for the waveguide that guides infrared photons **224** longitudinally in quantum waveguide infrared photodetector **200**. In an embodiment, with reference to FIG. **2** and FIG. **4**, such components include semiconductor contact layer **211**, buffer layer **210**, barrier layer **209**, photon absorption layer **208**, barrier layer **214**, semiconductor contact layer **206**, semiconductor member **202**, mode confinement layer **203**, and optional electrical insulator **230**. In an embodiment, with reference to FIG. **3**, such components also include core layer **215** and bottom cladding **216**.

Infrared photons **224** are received by quantum waveguide infrared photodetector **200** and propagate longitudinally primarily in photon absorption layer **208** with a transverse electromagnetic mode that is selectively confined by the hybrid waveguide structure indicated in the immediate prior paragraph to particular layers as indicated. FIG. **8** shows a map of a magnitude of an electromagnetic field for a transverse electromagnetic mode for infrared photons **224** propagating longitudinally in photon absorption layer **208** and layers proximate to photon absorption layer **208** for a transverse cross-section of infrared photons **224**. A wavelength of infrared photons **224** can be in the near infrared to far infrared region of the electromagnetic spectrum, e.g., from 700 nm to 1 mm, specifically from 1064 nm to 100 μm, and more specifically from 2000 nm to 20 μm. Further, infrared photons **224** may have electric and magnetic field orientations in any direction. It is contemplated that infrared photons **224** are converted to electrons **221** by absorption of infrared photons **224** by photon absorption layer **208**. An infrared absorption band of photon absorption layer **208** depends upon layers proximate to photon absorption layer **208**, wherein a composition and thickness of each layer in combination provides for a wavelength range of absorption and peak wavelength of absorption of photon absorption layer **208**. In this regard, the infrared absorption band of photon absorption layer **208** can be 700 nm to 1 mm, specifically from 1064 nm to 100 μm, and more specifically from 2000 nm to 20 μm. A peak of the infrared absorption band of photon absorption layer **208** can be from 700 nm to 1 mm, specifically from 1064 nm to 100 μm, and more specifically from 2000 nm to 20 μm. Without wishing to be bound by theory, it is believed that photon absorption layer **208** converts infrared photons **224** to electrons **221** by exciting electrons from a lower energy state in the photon absorption layer **208** to a higher energy state of the photon absorption layer **208**, where the lower energy state is bound, and electrons cannot exit the photon absorption layer **208** under an applied electric field and the higher energy state is coupled to the either semiconductor contact layer **206** or semiconductor contact layer **211** and electrons can exit the photon absorption layer **208** under an applied electric field.

Electrons **221** produced from infrared photons **224** have an energy provided by the potential difference subjected to electrons **221** by the first electrical potential applied to first conductor layer **213.1** and the second electrical potential applied to second conductor layer **213.2**. A voltage of the first potential can be from −100 volt (V) to 100 V, specifically from −10 V to 10 V, and more specifically from −5 V to 5 V. A voltage of the second potential can be from −100 volt (V) to 100 V, specifically from −10 V to 10 V, and more specifically from −5 V to 5 V. Accordingly, an electrical potential in photon absorption layer **208** to which infrared photons **224** and nascent electrons **221** produced therefrom can be from 0 V to 200 V, specifically from 0.1 V to 20 V, and more specifically from 1 V to 10 V so that an energy of electrons **221** can be from 0 electron volts (eV) to 200 eV, specifically from 0.1 eV to 20 eV, and more specifically from 1 eV to 10 eV.

Electrons **221** communicated from photon absorption layer **208** to conductor layer **213** or electrical contact pad **220** are issued from quantum waveguide infrared photodetector **200** as detector signal **227**. Detector signal **227** can be an electrical current from 1 pico ampere (pA) to 10 ampere (A), specifically from 10 pA to 1 A, and more specifically from 100 pA to 10 mA.

Quantum waveguide infrared photodetector **200** can include additional optical and electronic components including mirrors, lenses, optical fiber, electrical communication lines (e.g., coaxial cable) and the like.

It should be appreciated that quantum waveguide infrared photodetector **200** can be configured with layers formed on a gallium arsenide substrate and bonded to a silicon substrate. With reference to FIG. **2**, the silicon substrate can include an etched trench to isolate optical properties of the waveguide in quantum waveguide infrared photodetector **200** from the silicon substrate and provide a lower cladding of air, wherein this structure provides a high index of refraction contrast for the guided optical mode. With reference to FIG. **3**, quantum waveguide infrared photodetector **200** can include the waveguide on a silicon substrate coupled to the GaAs-based waveguide to tailor the optical confinement laterally. The waveguide core can include silicon or another material for selective absorption of wavelengths of infrared photons **224**, wherein the material can have low optical loss. A length of quantum waveguide infrared photodetector **200** can be selectively shortened so optical loss requirement can be minimized. A lower cladding shown in FIG. **3** can include a variety of materials that can ease fabrication such as including the substrate waveguide of silicon with a lower cladding of silicon dioxide. With reference to FIG. **4**, quantum waveguide infrared photodetector **200** can include a double bonding fabrication step to form a GaAs waveguide to provide longer wavelength detection and to tailor the confinement of optical modes independent of a ridge width (the combined widths of photon absorption layer **208**, barrier layer **209**, buffer layer **210**, semiconductor contact layer **211**, and barrier layer **214**) of quantum waveguide infrared photodetector **200**. Dimensions of quantum waveguide infrared photodetector **200** can control wavelength of operation via absorption of infrared photons **224**. In an embodiment, quantum waveguide infrared photodetector **200** with a suspended configuration shown in FIG. **4** can operate at 5.0 μm wavelength with a ridge width of (3.0±1.0) μm and a separation between the photon absorption layer **208**, the barrier layer **209**, the buffer layer **210**, the semiconductor contact layer **211**, and the barrier layer **214** and conductor layer **213.1** and conductor layer **213.3** of (2.5±0.5) μm. The conductor layer **213.2** can be narrower than the photon absorption layer **208**, the barrier layer **209**, the buffer layer **210**, the semiconductor contact layer **211**, and the barrier layer **214** by about 1.0 μm, to give a 500 nm offset on each side. The Si trench can be etched, e.g., to be 1.0 μm deep and as wide as (8.0±2.0) μm.

Quantum waveguide infrared photodetector **200** can be made in various ways. In an embodiment, a process for making quantum waveguide infrared photodetector **200** includes forming substrate **201** by providing a silicon wafer or a wafer of another material such as quartz or gallium arsenide; forming semiconductor member **202** on semiconductor contact layer **206** by contacting semiconductor contact layer **206** with a gaseous composition of gallium and arsenide atoms; forming mode confinement layer **203** by etching substrate **201** with a dry or wet etch chemistry in a patterned region that is wider than photon absorption layer **208**, barrier layer **209**, buffer layer **210**, semiconductor contact layer **211**, and barrier layer **214**; forming substrate gap surface **204** by etching substrate **201** with a dry or wet etch chemistry in a patterned region that is wider than photon absorption layer **208**, barrier layer **209**, buffer layer **210**, semiconductor contact layer **211**, and barrier layer **214**; forming semiconductor gap surface **205** by bonding to substrate **201** using a direct or interlayer surface bonding technique such as hydrophobic direct bonding; forming semiconductor contact layer **206** by contacting barrier layer **214** with a gaseous composition of gallium and arsenide atoms; forming semiconductor contact surface **207** by etching photon absorption layer **208**, barrier layer **209**, buffer layer **210**, semiconductor contact layer **211**, and barrier layer **214** with a dry or wet etch chemistry in a patterned region; forming photon absorption layer **208** by contacting barrier layer **209** with a gaseous composition of gallium and arsenide atoms and sometimes indium or aluminum atoms; forming barrier layer **209** by contacting buffer layer **210** with a gaseous composition of gallium, arsenide, and aluminum atoms; forming buffer layer **210** by contacting semiconductor contact layer **211** with a gaseous composition of gallium, arsenide, and aluminum atoms; forming semiconductor contact layer **211** by contacting semiconductor etch stop layer **222** with a gaseous composition of gallium and arsenide atoms and sometimes aluminum atoms; forming top contact surface **212** by etching semiconductor etch stop layer **222** with a dry or wet etch chemistry either patterned or not patterned; forming conductor layer **213** by physical or chemical vapor deposition over a patterned sacrificial layer; forming barrier layer **214** by contacting photon absorption layer **208** with a gaseous composition of gallium, arsenide, and aluminum atoms; forming core layer **215** by bonding core layer **215** to bottom cladding **216** using a direct or interlayer surface bonding technique (e.g., hydrophobic direct bonding) and etching core layer **215** with a dry or wet etch chemistry (e.g., boron trichloride plasma) in a patterned region; forming bottom cladding **216** by performing wet or dry thermal oxidation of substrate **201**; forming cladding air gap surface **217** by etching core layer **215** with a dry or wet etch chemistry in a patterned region; forming semiconductor air gap surface **218** by etching semiconductor member **202** with a dry or wet etch chemistry in a patterned region; forming semiconductor air gap surface **219** by bonding semiconductor contact layer **206** to semiconductor member **202** using a direct or interlayer surface bonding technique; and forming electrical contact pad **220** by forming electrical contact pad **220** using physical or chemical vapor deposition over a patterned sacrificial layer. The process also can include forming semiconductor etch stop layer **222** on gallium arsenide substrate **223** by contacting gallium arsenide substrate **223** with a gaseous composition of gallium, arsenide, and aluminum atoms, semiconductor etch stop layer **222** is an etch stop layer for selectively stopping an etchant from etching layers on which semiconductor etch stop layer **222** is disposed. Moreover, layers of first ply **228** can be formed on first ply substrate **223** that can be removed by etching.

In an embodiment, with reference to FIG. **9** to FIG. **18** for making quantum waveguide infrared photodetector **200** shown in FIG. **2**, with reference to FIG. **19** to FIG. **22** for making quantum waveguide infrared photodetector **200** shown in FIG. **3**, with reference to FIG. **23** to FIG. **28** for making quantum waveguide infrared photodetector **200** shown in FIG. **4**, and with reference to FIG. **29** to FIG. **31** for making quantum waveguide infrared photodetector **200** shown in FIG. **5**, a process for making quantum waveguide infrared photodetector **200** includes providing substrate **201** (step **300**); etching substrate **201** to form mode confinement layer **203** by patterning the substrate **201** with photoresist and etching with sulfur hexafluoride (step **301**); forming first ply **228** (step **302**) by disposing layers of gallium arsenide and aluminum gallium arsenide with molecular beam epitaxy on a gallium arsenide substrate; bonding first ply **228** to second ply **229** (step **303**) by hydrophobic direct bonding; removing first ply substrate **223** (step **304**) by wet etching with ammonium hydroxide, hydrochloric acid, and water; etching semiconductor contact layer **206**, barrier layer **214**, photon absorption layer **208**, barrier layer **209**, buffer layer **210**, and semiconductor contact layer **211** (step **305**) by patterning with photoresist and exposure to silicon tetrachloride plasma; forming conductor layer **213** (step **306**) by electron beam evaporation; forming electrical insulator **230** (step **307**) by spinning and exposing a photosensitive dielectric with a pattern; removing a portion of electrical insulator **230** (step **308**) by dry ashing with oxygen plasma; forming electrical contact pad **220** (step **309**) by electron beam evaporation; and removing a section of layers adjoining the quantum waveguide infrared photodetector **200** (step **310**) by etching with silicon tetrachloride plasma.

In an embodiment, with reference to FIG. **23** and FIG. **24**, the process for making quantum waveguide infrared photodetector **200** includes forming a preliminary bonded interface with a patterned air gap trench at the interface (step **298**) by etching the first wafer, growing a multilayer film on the second wafer, and then bonding the first wafer to the second wafer; and forming a planar thin membrane (step **299**) by removing the substrate from the second wafer and leaving the multilayer film bonded to the first wafer.

The process for making quantum waveguide infrared photodetector **200** also can include providing a substrate (step **311**) with epitaxially grown layers that form the entire quantum waveguide infrared photodetector **200**; etching semiconductor contact layer **206**, barrier layer **214**, photon absorption layer **208**, barrier layer **209**, buffer layer **210**, and semiconductor contact layer **211** (step **305**) by patterning with photoresist and exposure to silicon tetrachloride plasma; forming conductor layer **213** (step **306**) by electron beam evaporation; forming electrical insulator **230** (step **307**) by spinning and exposing a photosensitive dielectric with a pattern; removing a portion of electrical insulator **230** (step **308**) by dry ashing with oxygen plasma; forming electrical contact pad **220** (step **309**) by electron beam evaporation; and removing a section of layers adjoining the quantum waveguide infrared photodetector **200** (step **310**) by etching with silicon tetrachloride plasma.

Quantum waveguide infrared photodetector **200** has numerous advantageous and unexpected benefits and uses. In an embodiment, a process for detecting infrared photons by intersubband transitions in a semiconductor of photon absorption layer **208** with quantum waveguide infrared photodetector **200** includes: receiving, by photon absorption layer **208**, infrared photons **224**; propagating longitudinally infrared photons **224** along the longitudinal length of photon absorption layer **208**; converting, by photon absorption layer **208**, infrared photons **224** into electrons **221** by intersubband transitions in the semiconductor of photon absorption layer **208**; biasing first conductor layer **213.1** with the first electrical potential; biasing second conductor layer **213.2** with the second electrical potential; communicating electrons **221** from photon absorption layer **208** to first conductor layer **213.1** when the first electrical potential is more positive than the second electrical potential; and communicating electrons **221** from photon absorption layer **208** to second conductor layer **213.2** when the second electrical potential is more positive than the first electrical potential to detect the infrared photons, wherein an electrical current produced by electrons **221** is proportional to the amount of absorption of infrared photons **224** in photon absorption layer **208**. The process also can include communicating electrons **221** as detector signal **227** from first conductor layer **213.1** to current meter **226** when the first electrical potential is more positive than the second electrical potential. The process also can include communicating the electrons **221** as detector signal **227** from second conductor layer **213.2** to current meter **226** when the second electrical potential is more positive than the first electrical potential. A fluence of infrared photons **224** received by quantum waveguide infrared photodetector **200** can be determined from detector signal **227** by measuring and integrating the electrical current produced by the quantum waveguide infrared photodetector **200** under a voltage bias over time.

Quantum waveguide infrared photodetector **200** and processes disclosed herein have numerous beneficial uses, including room temperature infrared detection at high speed, high sensitivity, and in a compact package. Advantageously, quantum waveguide infrared photodetector **200** overcomes limitations of technical deficiencies of conventional compositions such as low absorption per quantum well, leading to large numbers of quantum wells and associated high dark current and noise current. Further, the quantum waveguide infrared photodetector reduces the cross-sectional area of the photon absorbing layer **208** in the direction of current flow and subsequently the current noise.

Quantum waveguide infrared photodetector **200** and processes herein unexpectedly produce higher detection sensitivity with lower current noise than conventional technologies at the same temperature. Moreover, quantum waveguide infrared photodetector **200** provides equivalent detection sensitivity and current noise at a higher temperature, e.g., room temperature, compared to cryogenic temperature operation of conventional technologies. Conventional technologies include surface normal irradiated quantum well infrared photodetectors (QWIPs), quantum dot infrared photodetectors (QDIPs), quantum cascade detectors (QCDs), inter-band cascade detectors (ICDs), mercury-cadmium-telluride detectors (MCTs), deuterated L-alanine doped triglycine sulfate (DLaTGS), and pyroelectric detectors. These conventional detectors work for lower-speed detection applications. Beneficially, quantum waveguide infrared photodetector **200** has comparatively higher performance than these conventional technologies in terms of detection speed, sensitivity, and noise level and a lower cost to fabricate and produce. Additionally, a QWIP with surface normal detection can be formatted into infrared focal plane arrays for infrared cameras. Quantum waveguide infrared photodetector **200** detects light incident on a single detector element in the plane of the material growth and uses an absorbing region for intersubband transition in a quantum well and waveguiding has been developed for photodiodes using inter-band absorption. Unexpectedly, quantum waveguide infrared photodetector **200** has high efficiency with high index contrast on a silicon substrate. Quantum waveguide infrared photodetector **200** is made by wafer bonding photodetector material to a separate wafer rather than fabricating the detector on a native substrate on which QWIP layers are grown. As a result, quantum waveguide infrared photodetector **200** can be formed with a decrease in the number of quantum wells and a decrease in the cross-sectional area of current flow compared with conventional devices, while maintaining at least as high optical absorption efficiency as conventional devices. Accordingly, quantum waveguide infrared photodetector **200** has greater responsivity, less dark current noise, and greater signal-to-noise ratio than conventional devices.

The articles and processes herein are illustrated further by the following Example, which is non-limiting.

EXAMPLE

Layers for an exemplary quantum waveguide infrared photodetector **200** are listed in the Table. A primary absorbing region includes $In_{0.1}Ga_{0.9}As$ layers proximate to $Al_{0.4}Ga_{0.6}As$ layers, wherein the configuration absorbs infrared light near 5.0 μm wavelength with a bandwidth of about 100 nm. Changing a thickness of the $In_{0.1}Ga_{0.9}As$ layer to match an energy difference between the $In_{0.1}Ga_{0.9}As$ quantum well and adjacent $Al_{0.4}Ga_{0.6}As$ barrier layer provides selective absorption of a different central absorption wavelength.

TABLE

Element	Material	Thickness (nm)	Doping (cm^{-3})
semiconductor member 202	GaAs	900	Intrinsic
semiconductor contact layer 206	GaAs	200	2×10^{18}
barrier layer 214	$A_{0.4}Ga_{0.6}As$	40	Intrinsic
photon absorption layer 208	$In_{0.1}Ga_{0.9}As$	0.5	Intrinsic
photon absorption layer 208	$In_{0.1}Ga_{0.9}As$	2.85	2×10^{18}
photon absorption layer 208	$In_{0.1}Ga_{0.9}As$	0.5	Intrinsic
barrier layer 209	$Al_{0.4}Ga_{0.6}As$	400	Intrinsic
buffer layer 210	$Al_{0.8\ to\ 0.4}Ga_{0.2\ to\ 0.6}As$	200	Intrinsic
buffer layer 210	$Al_{0.8}Ga_{0.2}As$	3000	Intrinsic
semiconductor contact layer 211	GaAs	50	2×10^{18}
semiconductor etch stop layer 222	$Al_{0.8}Ga_{0.2}As$	150	Intrinsic
first ply substrate 223	GaAs substrate	625×10^{3}	Intrinsic

While one or more embodiments have been shown and described, modifications and substitutions may be made thereto without departing from the spirit and scope of the invention. Accordingly, it is to be understood that the present invention has been described by way of illustrations and not limitation. Embodiments herein can be used independently or can be combined.

All ranges disclosed herein are inclusive of the endpoints, and the endpoints are independently combinable with each other. The ranges are continuous and thus contain every value and subset thereof in the range. Unless otherwise stated or contextually inapplicable, all percentages, when expressing a quantity, are weight percentages. The suffix "(s)" as used herein is intended to include both the singular and the plural of the term that it modifies, thereby including at least one of that term (e.g., the colorant(s) includes at least one colorants). "Optional" or "optionally" means that the subsequently described event or circumstance can or cannot occur, and that the description includes instances where the event occurs and instances where it does not. As used herein, "combination" is inclusive of blends, mixtures, alloys, reaction products, and the like.

As used herein, "a combination thereof" refers to a combination comprising at least one of the named constituents, components, compounds, or elements, optionally together with one or more of the same class of constituents, components, compounds, or elements.

All references are incorporated herein by reference.

The use of the terms "a" and "an" and "the" and similar referents in the context of describing the invention (especially in the context of the following claims) are to be construed to cover both the singular and the plural, unless otherwise indicated herein or clearly contradicted by context. "Or" means "and/or." It should further be noted that the terms "first," "second," "primary," "secondary," and the like herein do not denote any order, quantity, or importance, but rather are used to distinguish one element from another. The modifier "about" used in connection with a quantity is inclusive of the stated value and has the meaning dictated by the context (e.g., it includes the degree of error associated with measurement of the particular quantity). The conjunction "or" is used to link objects of a list or alternatives and is not disjunctive; rather the elements can be used separately or can be combined together under appropriate circumstances.

What is claimed is:

1. A quantum waveguide infrared photodetector for detecting infrared photons by intersubband transitions in a semiconductor of a photon absorption layer, the quantum waveguide infrared photodetector comprising:

the photon absorption layer that receives infrared photons propagating longitudinally along a longitudinal length of the photon absorption layer, converts the infrared photons into electrons, and communicates the electrons to a conductor layer;

a barrier layer on which the photon absorption layer is disposed;

a first semiconductor contact layer on which the barrier layer is disposed;

a semiconductor member on which the semiconductor contact layer is disposed;

a substrate on which the semiconductor member is disposed;

a barrier layer disposed on the photon absorption layer;

a buffer layer disposed on the barrier layer;

a second semiconductor contact layer disposed on the buffer layer;

a first conductor layer disposed on the first semiconductor contact layer and that receives a first electrical potential; and

a second conductor layer disposed on the second semiconductor contact layer and that receives a second electrical potential,

wherein electrons produced by the photon absorption layer in response to receipt of the infrared photons are communicated from the photon absorption layer:

to the first conductor layer when the first electrical potential is more positive than the second electrical potential, and to the second conductor layer when the second electrical potential is more positive than the first electrical potential, and

wherein an electrical current produced by the electrons is proportional to an amount of absorption of the infrared photons in the photon absorption layer.

2. The quantum waveguide infrared photodetector of claim **1**, further comprising a mode confinement layer interposed between the substrate and the semiconductor member and bounded by surfaces of the substrate and the semiconductor member.

3. The quantum waveguide infrared photodetector of claim **2**, further comprising a second mode confinement layer disposed in semiconductor member, interposed between the semiconductor member and the semiconductor contact layer, and bounded by surfaces of the semiconductor member and the semiconductor contact layer.

4. The quantum waveguide infrared photodetector of claim **1**, further comprising a core layer interposed between the substrate and the semiconductor member.

5. The quantum waveguide infrared photodetector of claim **4**, further comprising a bottom cladding interposed between the core layer and the substrate.

6. The quantum waveguide infrared photodetector of claim **5**, further comprising a mode confinement layer disposed in core layer and interposed between the bottom cladding and the semiconductor member.

7. The quantum waveguide infrared photodetector of claim **6**, wherein the mode confinement layer is bounded by surfaces of the bottom cladding, the core layer, and the semiconductor member.

8. The quantum waveguide infrared photodetector of claim **1**, further comprising a first electrical contact pad disposed on the substrate and the first conductor layer and in electrical communication with the first conductor layer, such that the first electrical contact pad receives the first electrical potential for electrically biasing the first conductor layer.

9. The quantum waveguide infrared photodetector of claim **8**, further comprising a second electrical contact pad disposed on the substrate and the second conductor layer and in electrical communication with the second conductor layer, such that the second electrical contact pad receives the second electrical potential for electrically biasing the second conductor layer.

10. The quantum waveguide infrared photodetector of claim **1**, further comprising an electrical insulator disposed on the semiconductor contact layer and the semiconductor contact layer and that electrically insulates the first conductor layer from the second conductor layer.

11. The quantum waveguide infrared photodetector of claim **1**, further comprising an electrical bias supply in electrical communication with the first conductor layer and the second conductor layer, wherein the electrical bias supply provides the first electrical potential to the first conductor layer and the second electrical potential to the second conductor layer.

12. The quantum waveguide infrared photodetector of claim **11**, further comprising a current meter in electrical communication with the first conductor layer and the electrical bias supply, wherein the current meter receives a detector signal and determines the amount of electrical current from the detector signal.

13. The quantum waveguide infrared photodetector of claim **1**, wherein the photon absorption layer comprises a quantum well, quantum dots, or a quantum dash.

14. A process for detecting infrared photons by intersubband transitions in a semiconductor of a photon absorption layer with the quantum waveguide infrared photodetector of claim **1**, the process comprising:

receiving, by the photon absorption layer, the infrared photons;

propagating longitudinally the infrared photons along the longitudinal length of the photon absorption layer;

converting, by the photon absorption layer, the infrared photons into electrons by intersubband transitions in the semiconductor of the photon absorption layer;

biasing the first conductor layer with the first electrical potential;

biasing the second conductor layer with the second electrical potential;

communicating the electrons from the photon absorption layer to the first conductor layer when the first electrical potential is more positive than the second electrical potential; and

communicating the electrons from the photon absorption layer to the second conductor layer when the second electrical potential is more positive than the first electrical potential to detect the infrared photons,

wherein an electrical current produced by the electrons is proportional to the amount of absorption of the infrared photons in the photon absorption layer.

15. The process of claim **14**, further comprising communicating the electrons as a detector signal from the first conductor layer to a current meter when the first electrical potential is more positive than the second electrical potential.

16. The process of claim **14**, further comprising communicating the electrons as a detector signal from the second conductor layer to a current meter when the second electrical potential is more positive than the first electrical potential.

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