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Van Orden

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(54) **RING MODULATOR WITH RIB RING OPTICAL WAVEGUIDE AND INTERDIGITATED PN JUNCTION DIODE**

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Publication Classification

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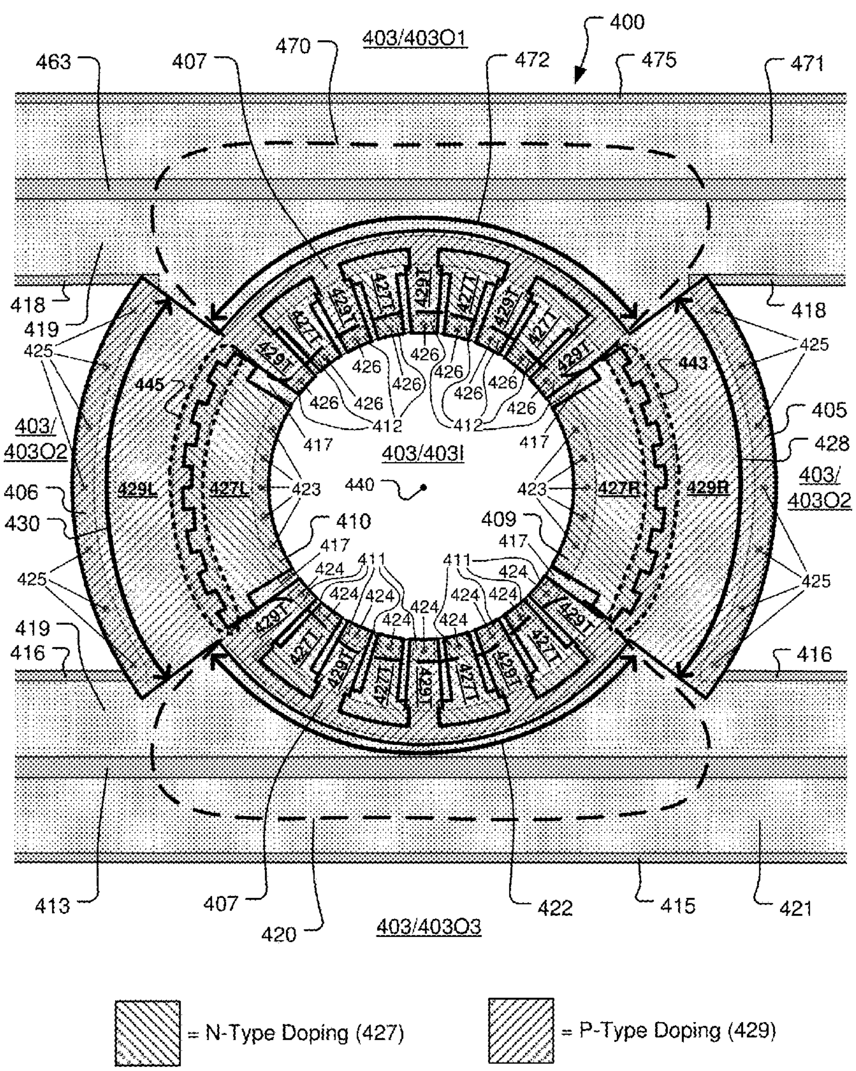
G02F 1/025 (2006.01)

(52) **U.S. Cl.**
CPC ***G02F 1/025*** (2013.01); *G02F 2201/063* (2013.01); *G02F 2201/124* (2013.01); *G02F 2202/06* (2013.01)

(57) **ABSTRACT**

A photonic integrated circuit includes a first ring-shaped optical waveguide optically coupled to both a second optical waveguide and a third optical waveguide within a first optical coupling region and a second optical coupling region, respectively. An inner silicon region is formed along an inner side of the first ring-shaped optical waveguide. Tab-shaped N-type doping regions and tab-shaped P-type doping regions are formed in alternating positions within the first ring-shaped optical waveguide and the inner silicon region within the first optical coupling region to form a first interdigitated PN diode configuration within the first optical coupling region. Tab-shaped N-type doping regions and tab-shaped P-type doping regions are also formed in alternating positions within the first ring-shaped optical waveguide and the inner silicon region within the second optical coupling region to form a second interdigitated PN diode configuration within the second optical coupling region.



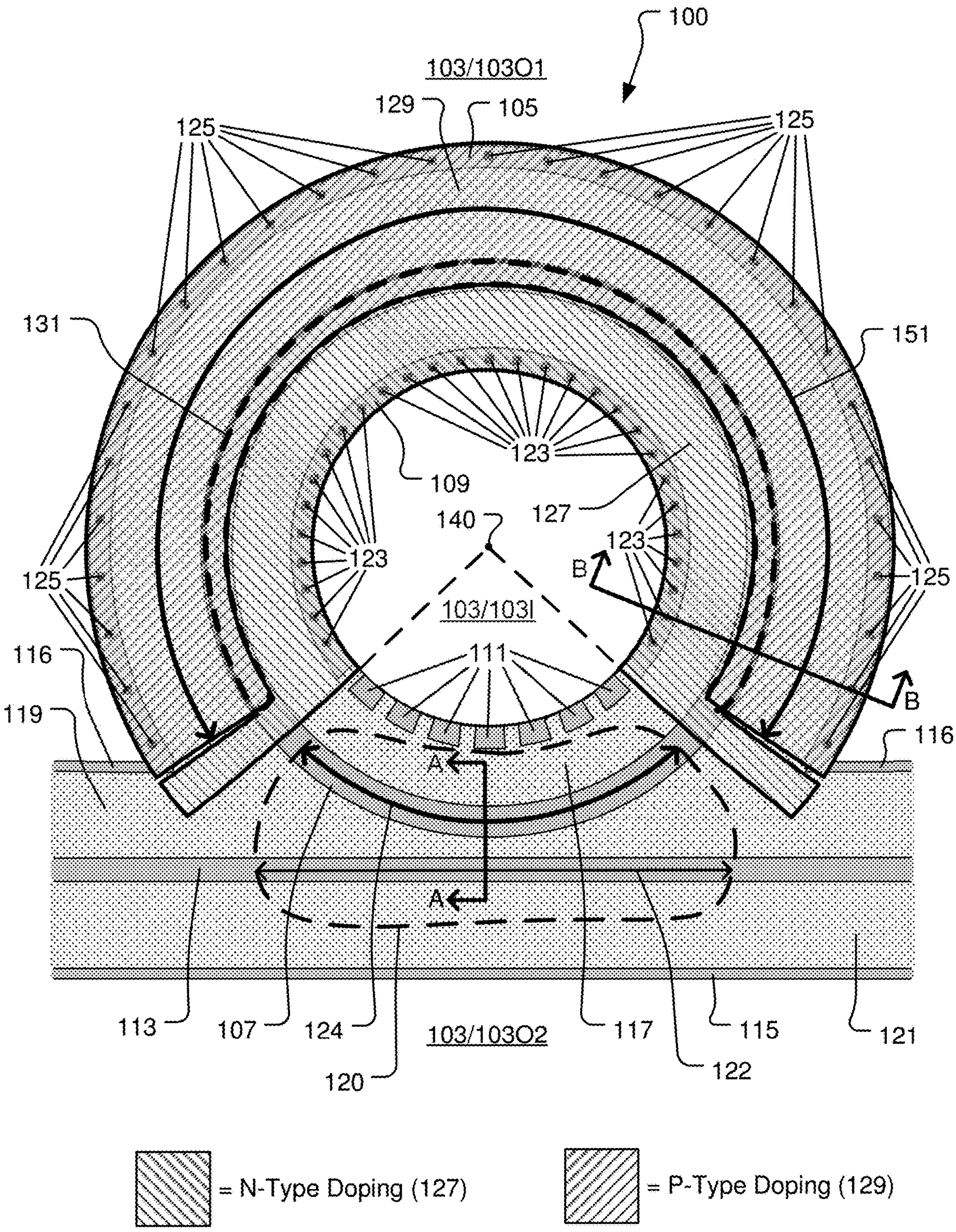
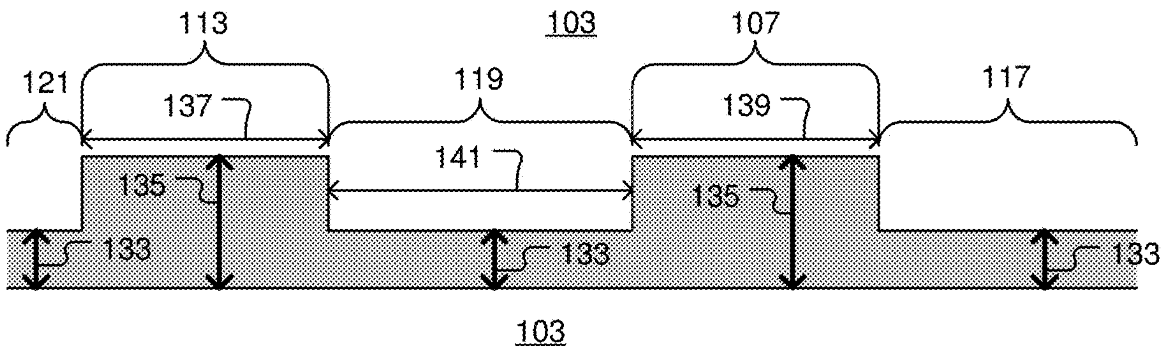
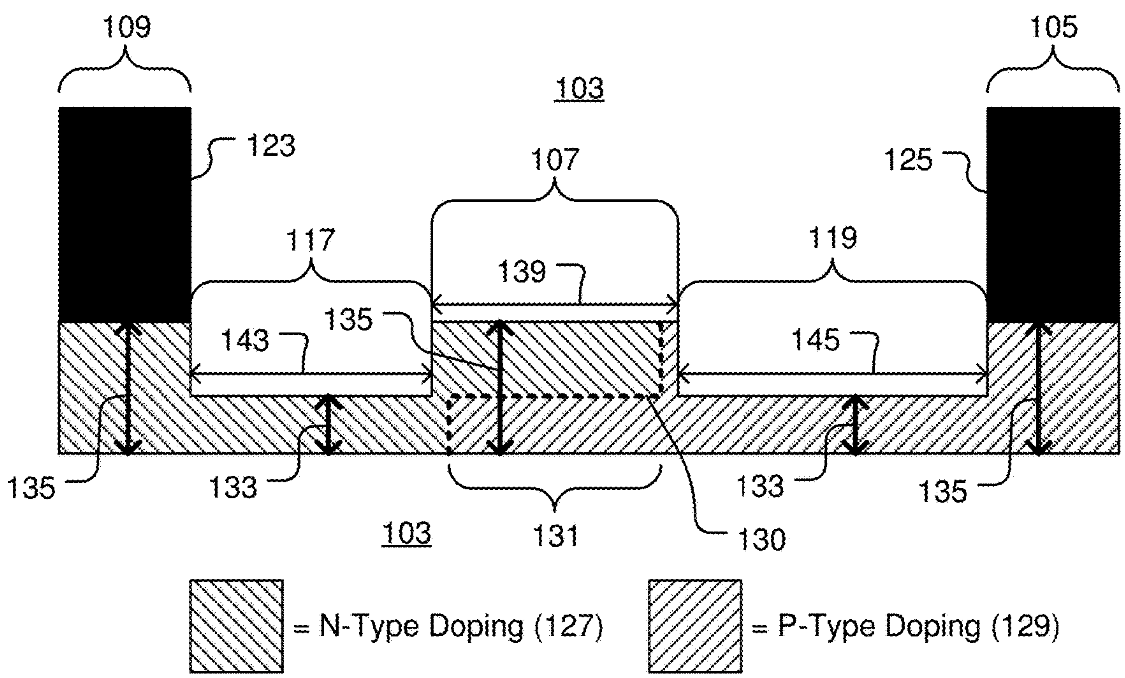

100
103/103O1
129
105
125
125
131
151
123
109
127
140
123
123
B
125
125
103/103I
111
116
B
119
116
A
A
113
107
124
103/103O2
117
115
121
120
122
= N-Type Doping (127)
= P-Type Doping (129)

Fig. 1A



(View A-A)

Fig. 1B



(View B-B)

Fig. 1C

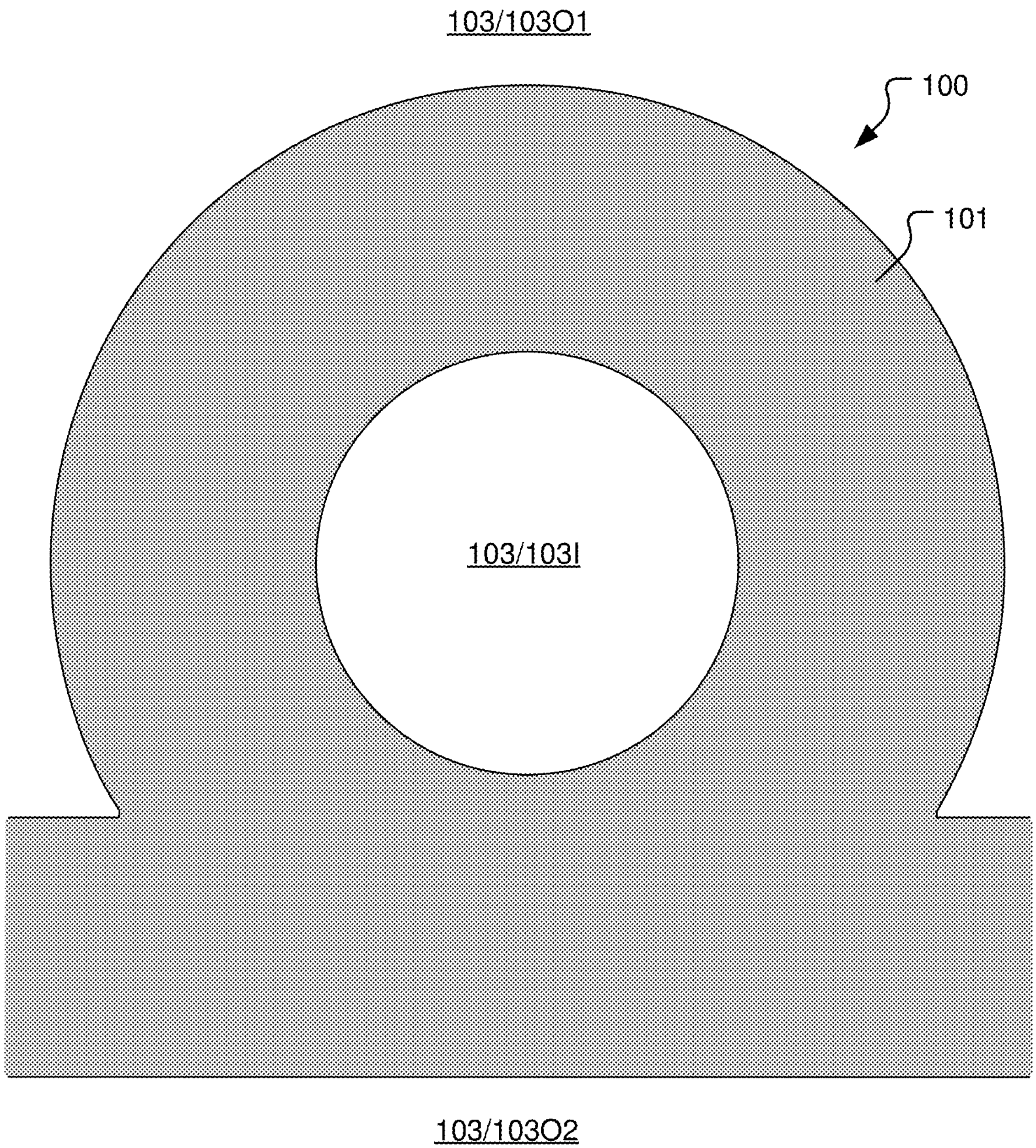


Fig. 1D

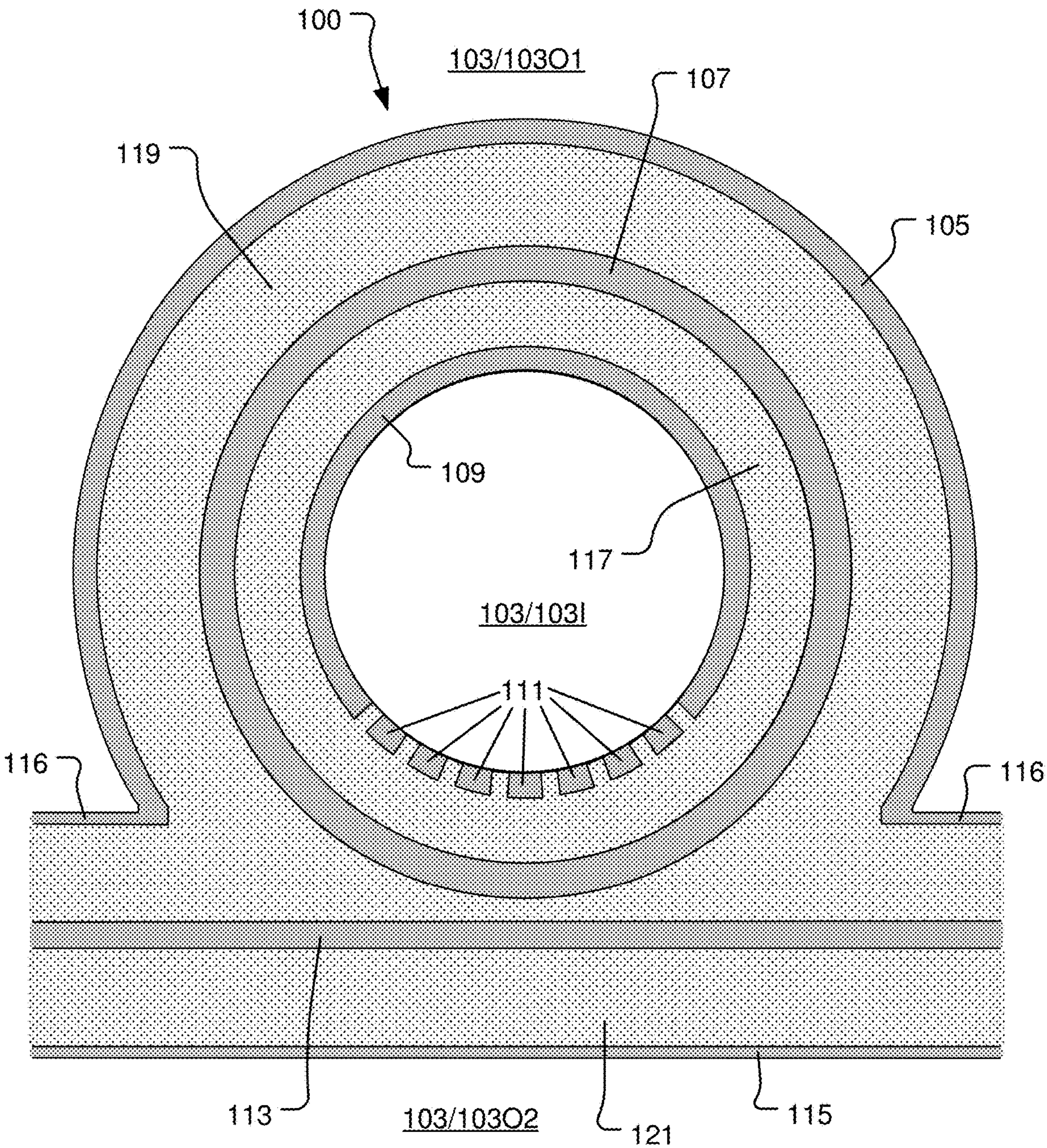

100
103/103O1
107
119
105
109
117
103/103I
111
116
116
113
103/103O2
121
115

Fig. 1E

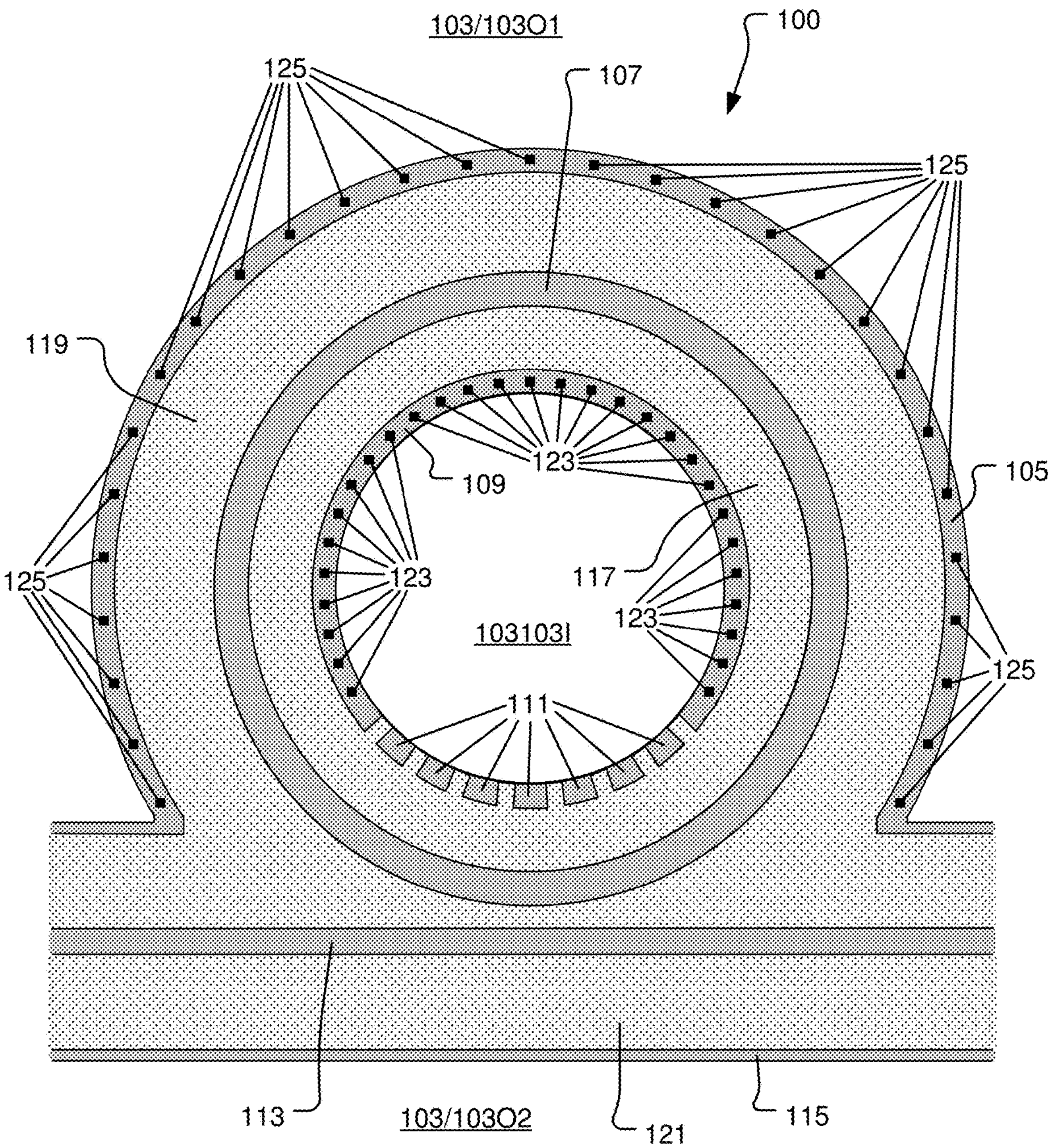

103/103O1
100
125
107
125
119
123
109
105
117
125
123
123
103103I
125
111
113
103/103O2
121
115

Fig. 1F

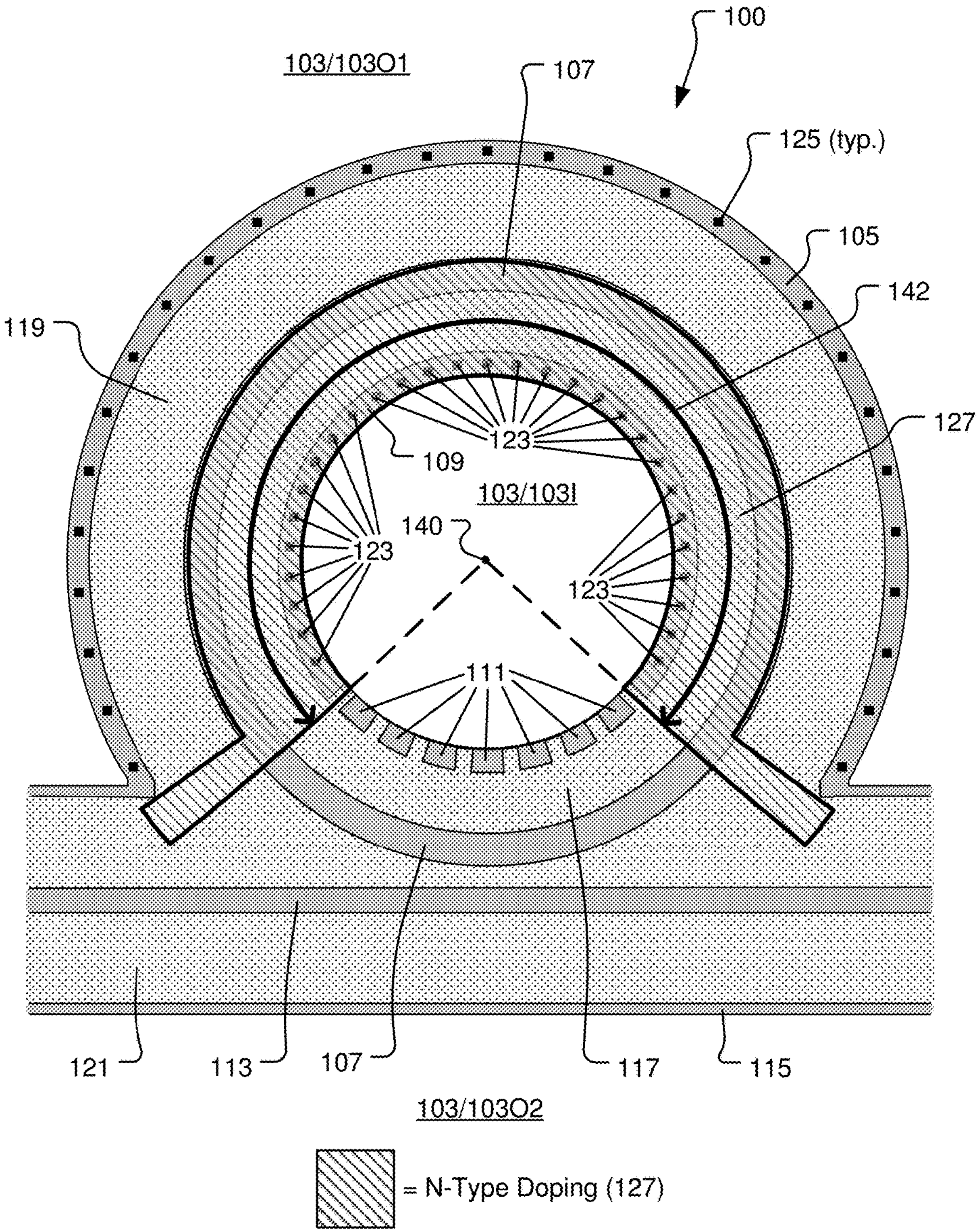

100
103/103O1
107
125 (typ.)
105
142
119
127
123
109
103/103I
140
123
123
111
121
113
107
117
115
103/103O2
= N-Type Doping (127)

Fig. 1G

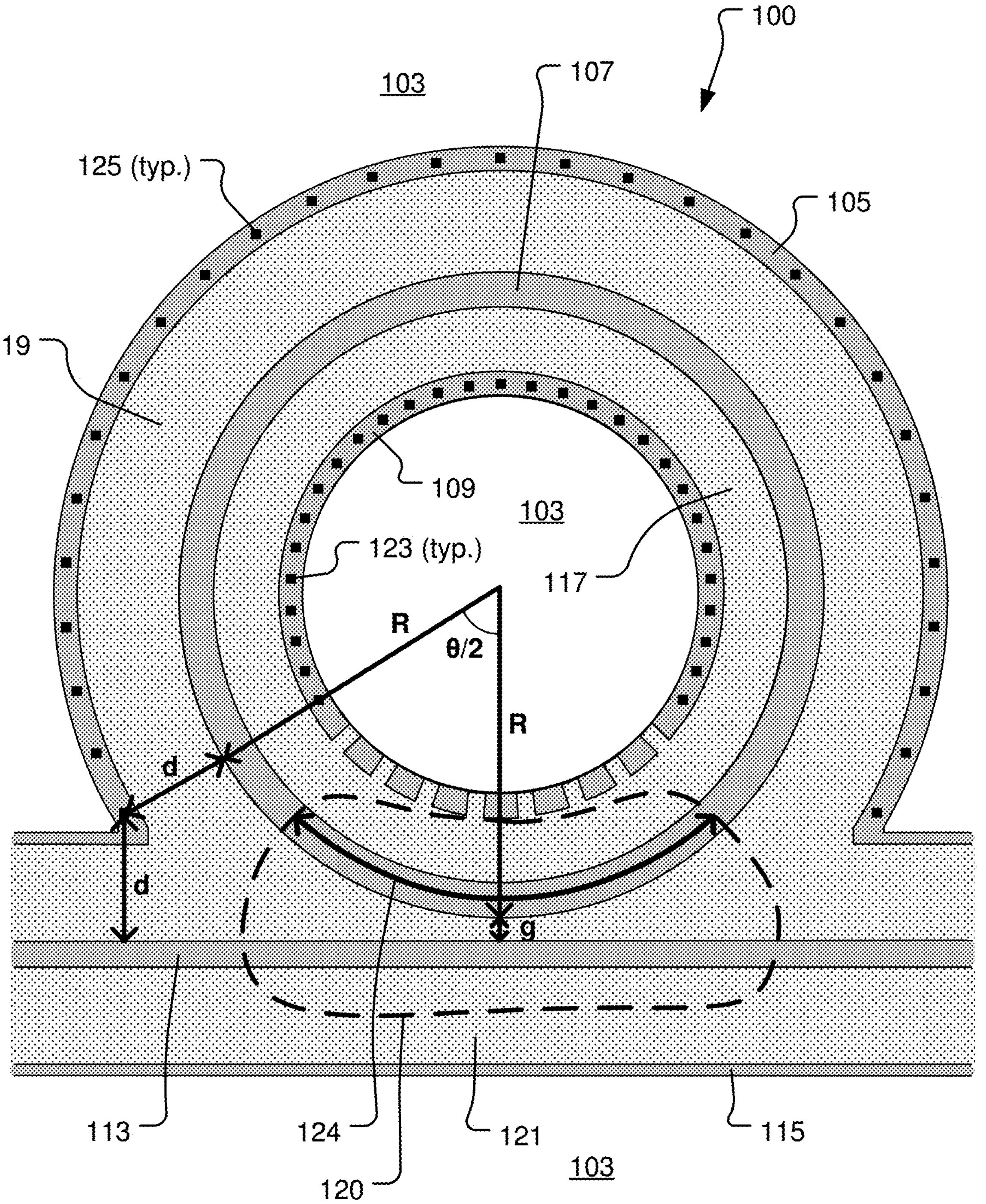

100
103
107
125 (typ.)
105
119
109
103
123 (typ.)
117
R
θ/2
R
d
d
g
113
124
121
115
120
103

Fig. 2A

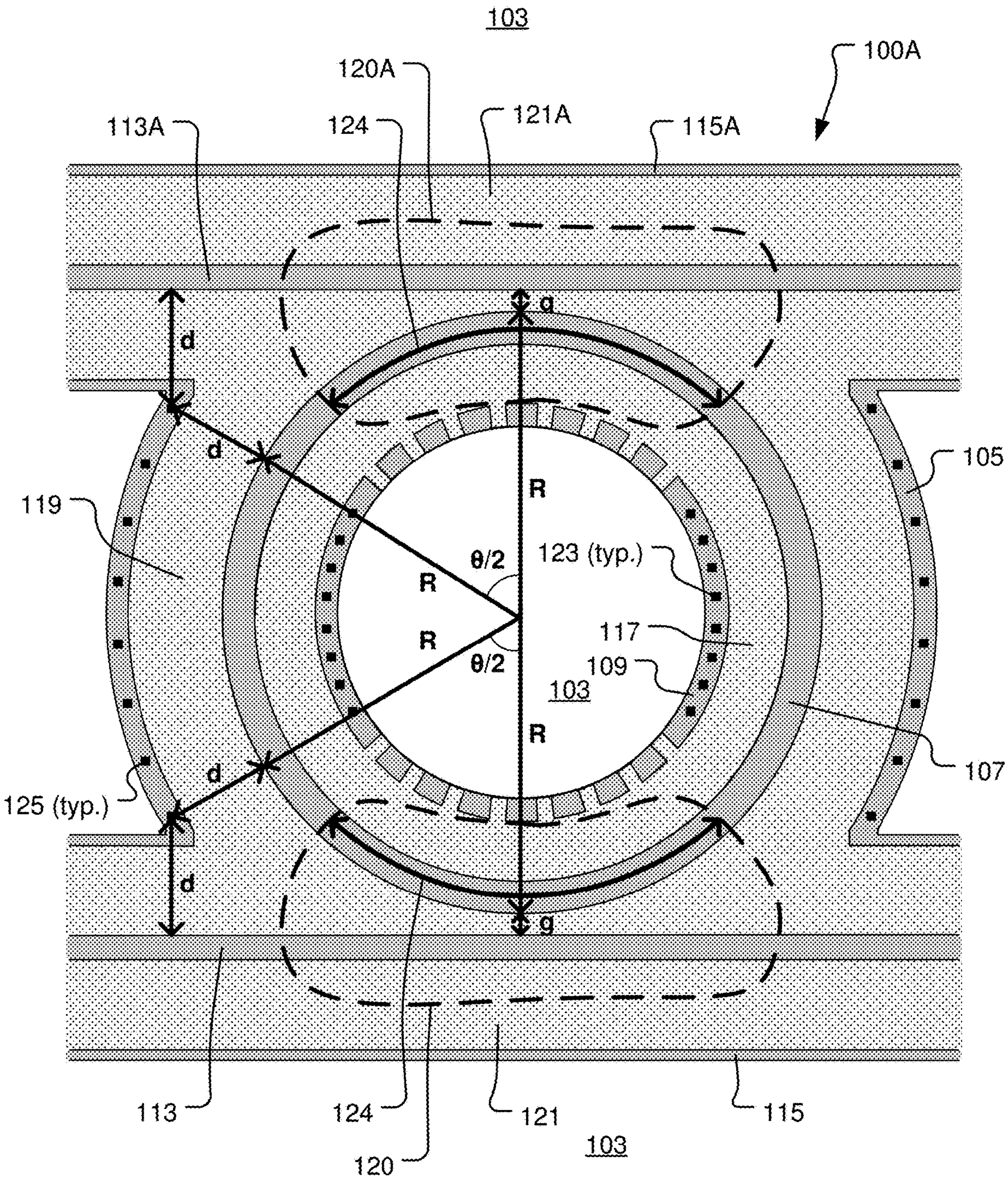

103
100A
120A
124
121A
115A
113A
g
d
d
R
105
119
θ/2
123 (typ.)
R
R
117
θ/2
109
103
R
107
d
125 (typ.)
d
g
113
124
121
115
103
120

Fig. 2B

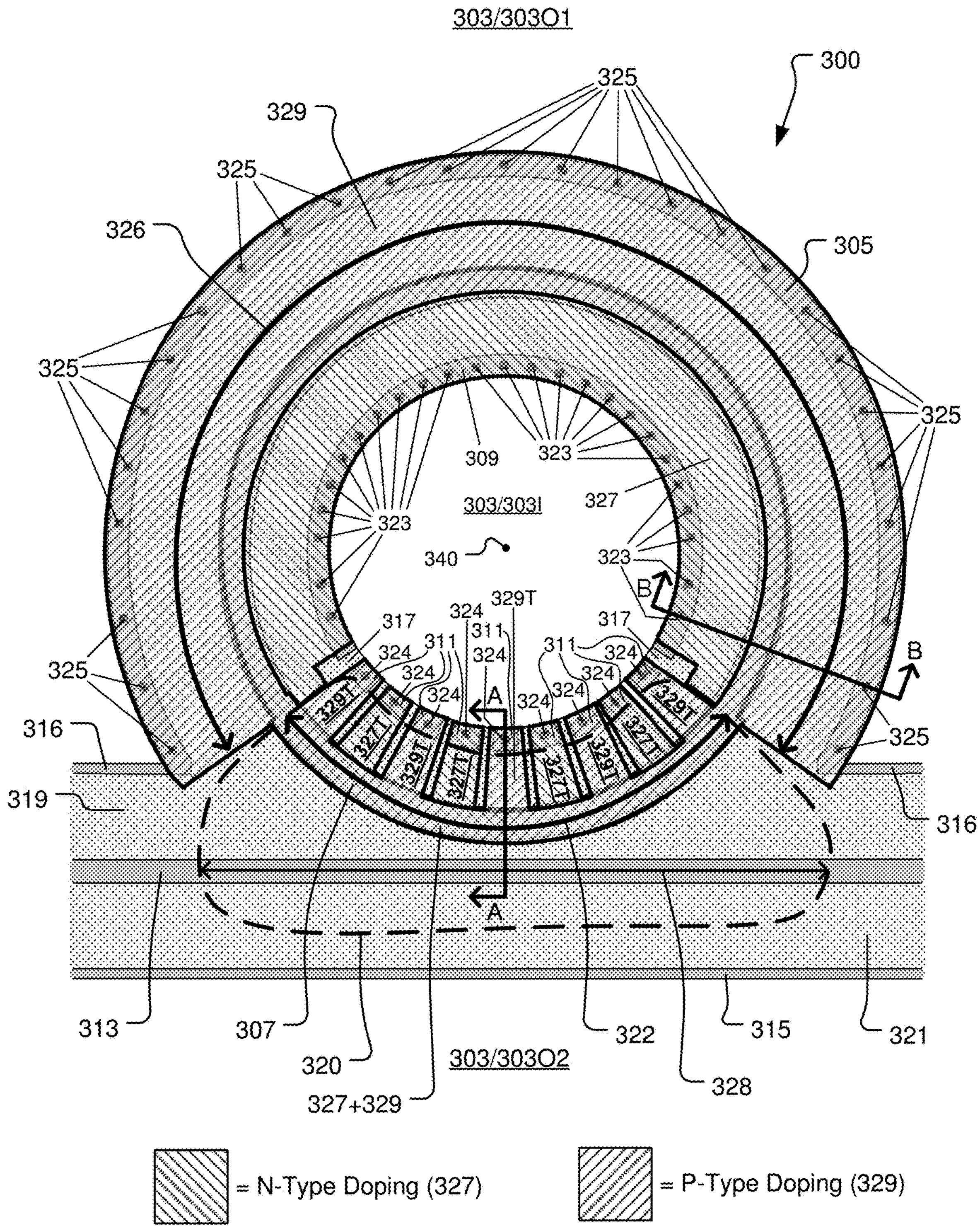

303/303O1
300
325
329
325
326
305
325
325
309
323
303/303I
327
323
340
323
329T
324
311
317
317
324
311
324
311
324
324
324
324
324
325
329T
327T
329T
327T
327T
329T
327T
329T
A
B
B
325
316
319
316
313
307
320
322
315
321
328
303/303O2
327+329
A
= N-Type Doping (327)
= P-Type Doping (329)

Fig. 3A

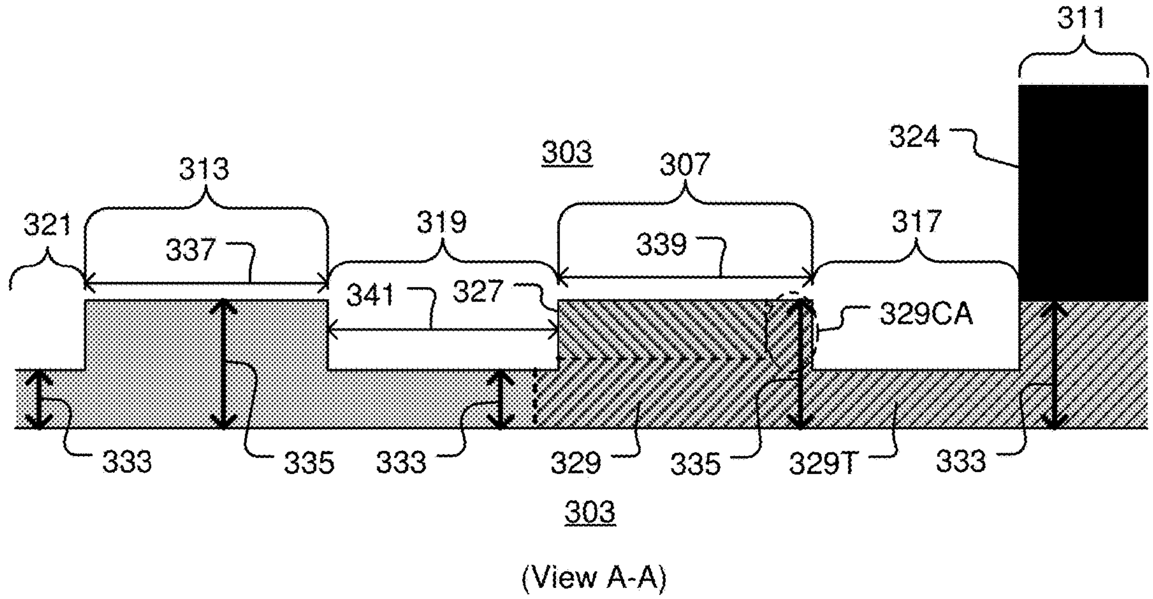

311
324
303
313
307
321
337
319
339
317
341
327
329CA
333
335
333
329
335
329T
333
303
(View A-A)

Fig. 3B

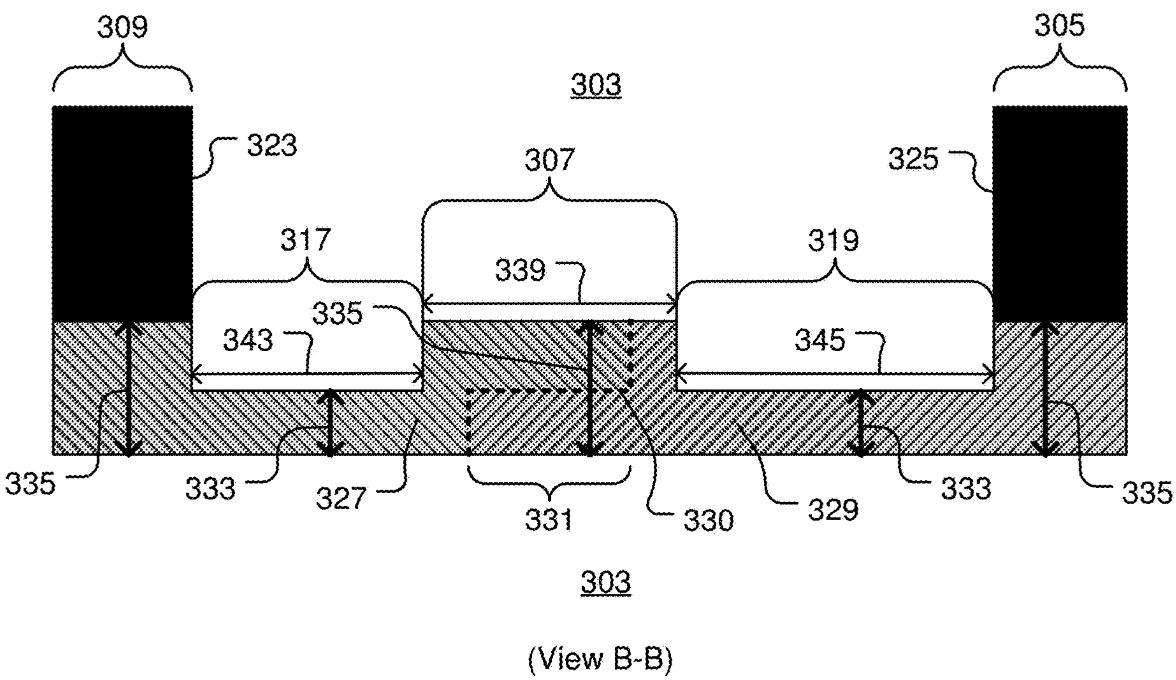

309
305
303
323
325
307
317
319
339
335
343
345
335
333
327
331
330
329
333
335
303
(View B-B)

Fig. 3C

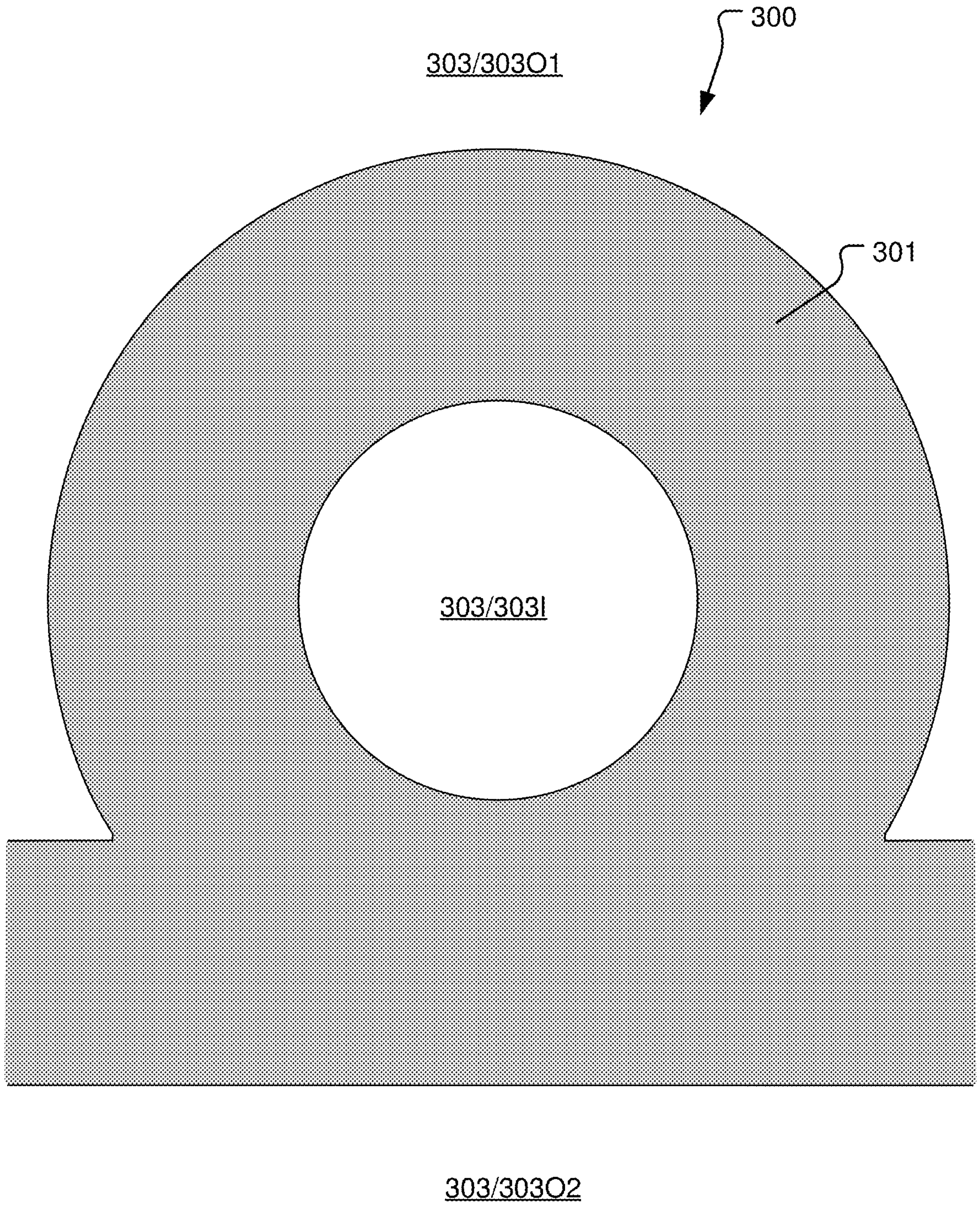


Fig. 3D

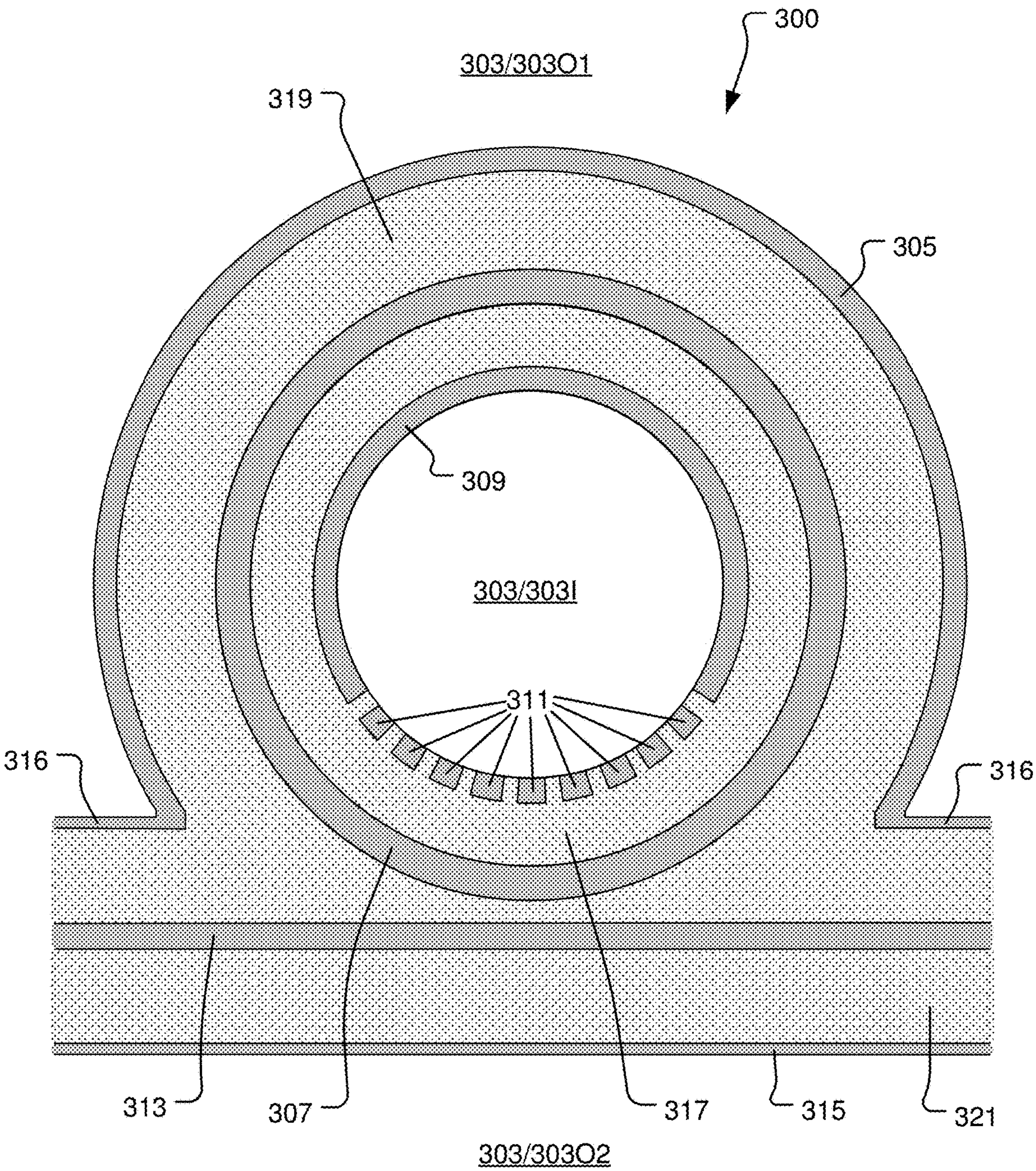

300
303/303O1
319
305
309
303/303I
311
316
316
313
307
317
315
321
303/303O2

Fig. 3E

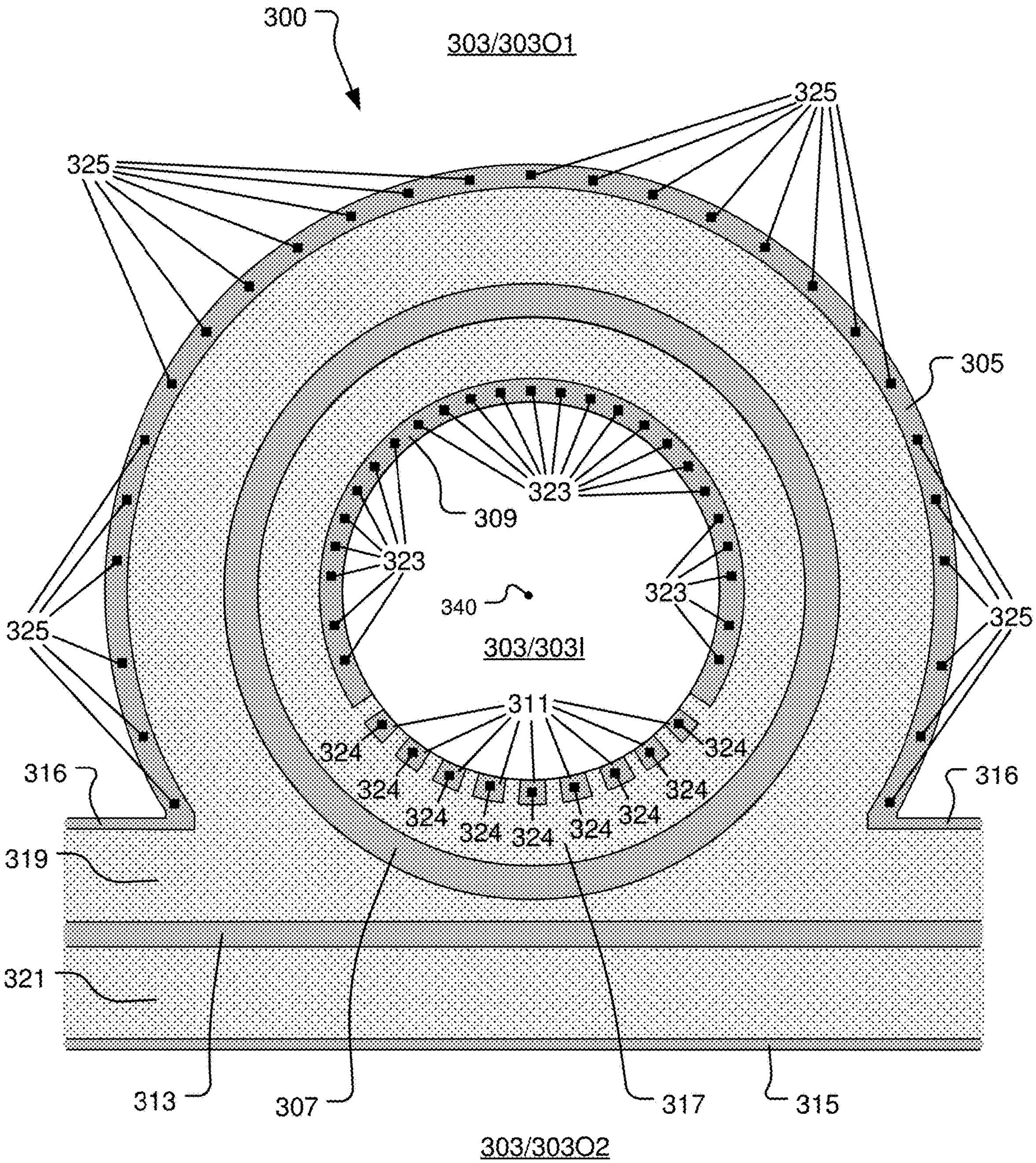

300
303/303O1
325
325
305
323
309
323
323
340
303/303I
325
325
311
324
324
324
324
324
324
324
324
324
324
316
316
319
321
313
307
317
315
303/303O2

Fig. 3F

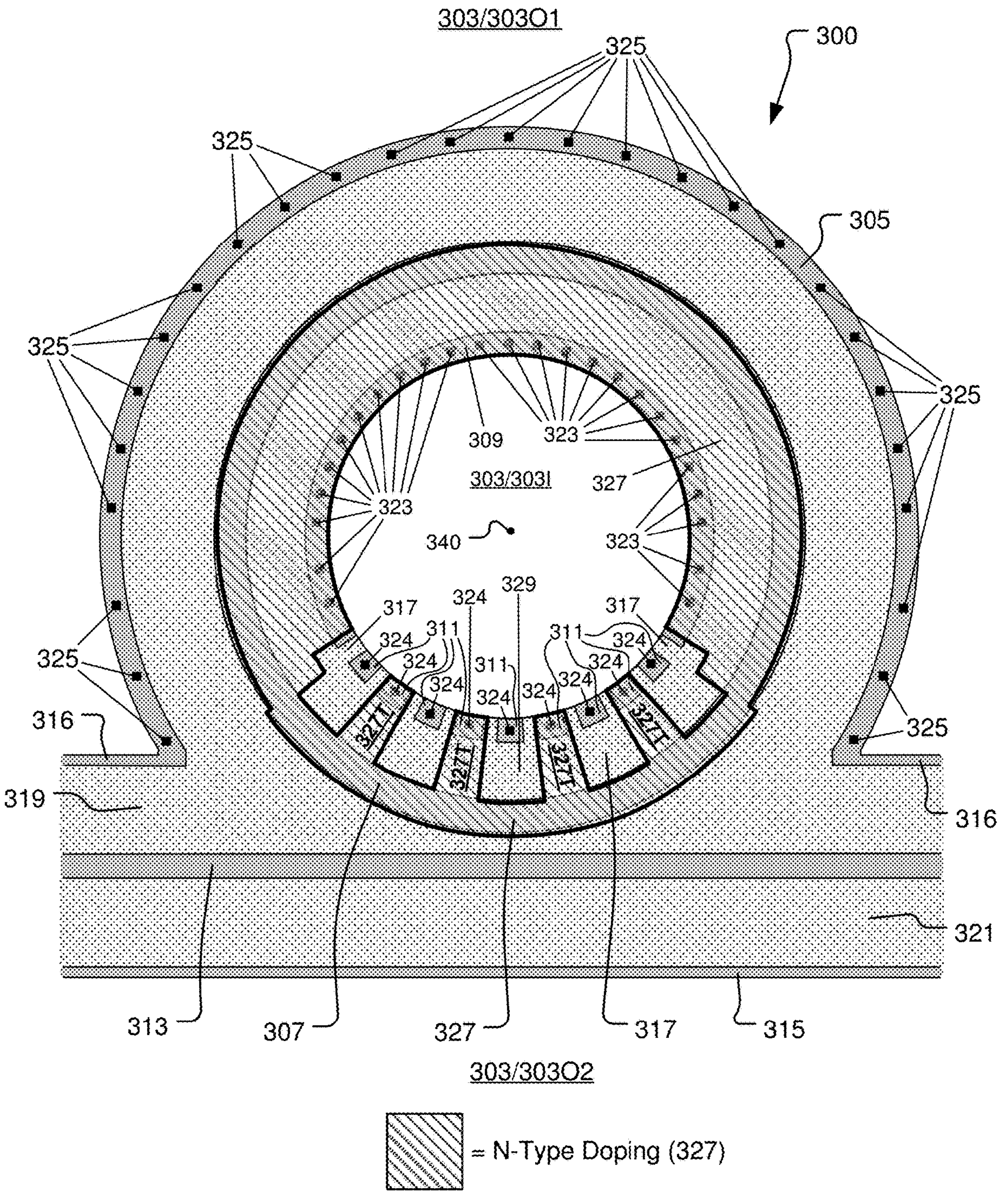

303/303O1
300
325
325
305
325
325
309
323
303/303I
327
323
340
323
329
317
324
317
311
324
311
324
311
324
324
324
324
324
324
327T
327T
327T
327T
325
316
325
319
316
321
313
307
327
317
315
303/303O2
= N-Type Doping (327)

Fig. 3G

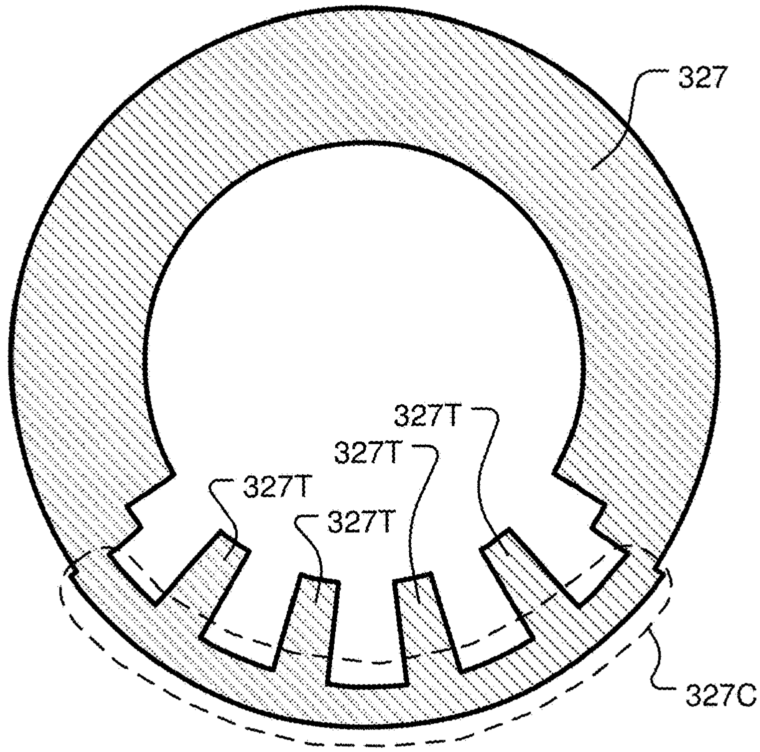

327
327T
327T
327T
327T
327C

Fig. 3H

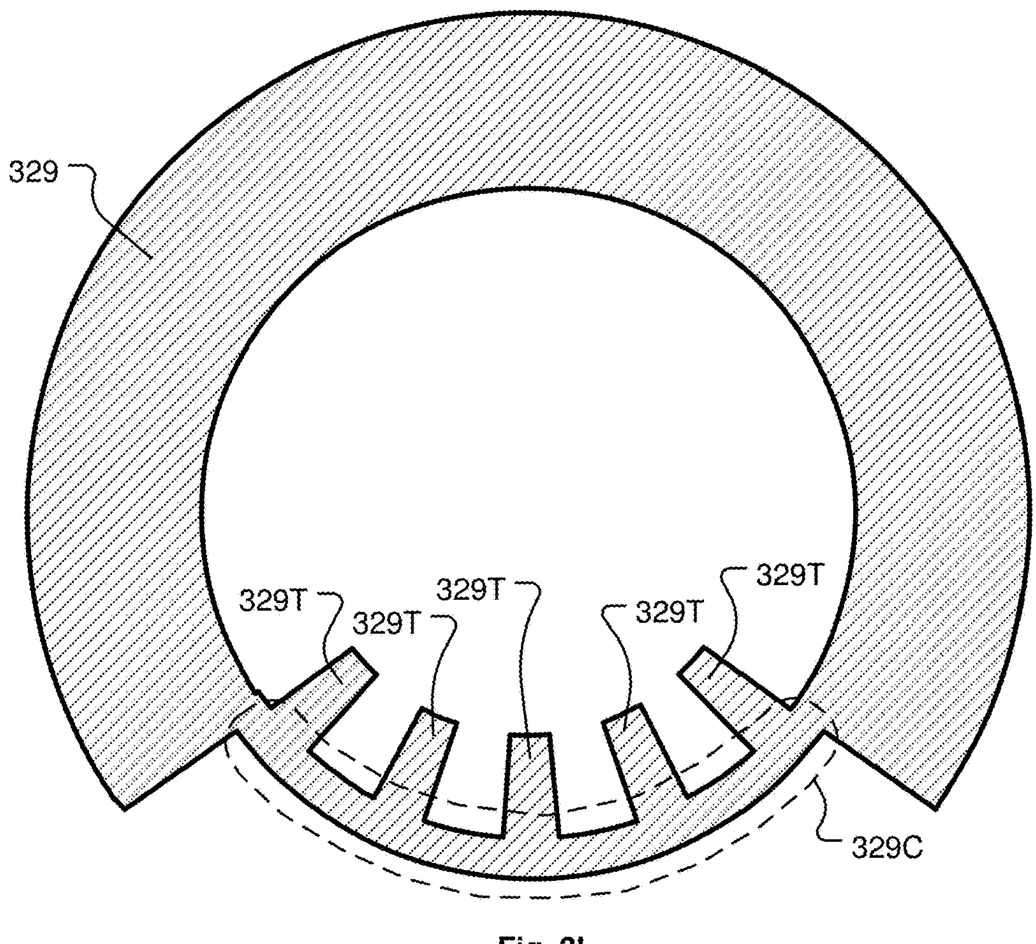

329
329T
329T
329T
329T
329T
329C

Fig. 3I

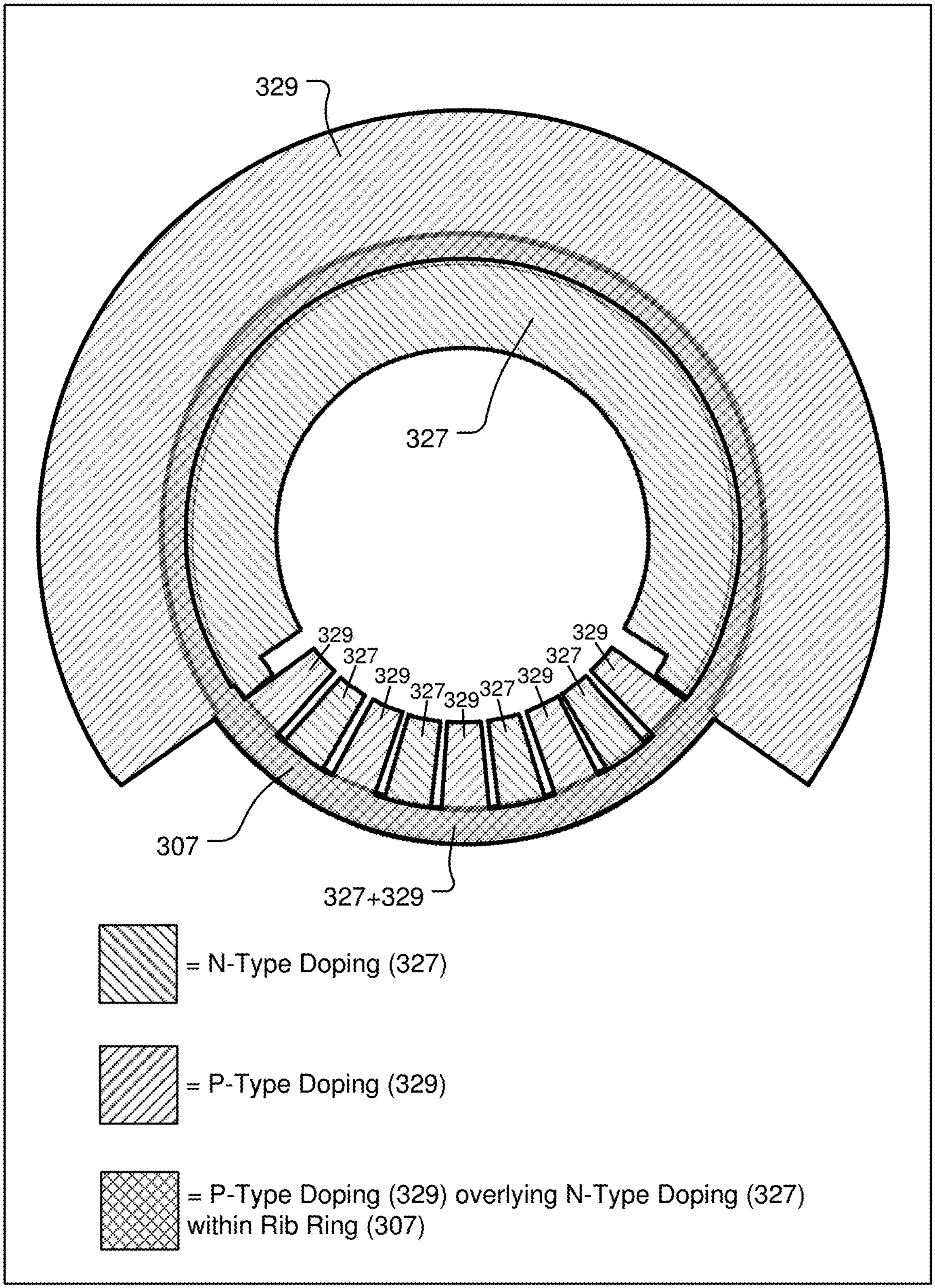

329
327
329
327
329
327
329
327
329
327
329
307
327+329
= N-Type Doping (327)
= P-Type Doping (329)
= P-Type Doping (329) overlying N-Type Doping (327) within Rib Ring (307)

Fig. 3J

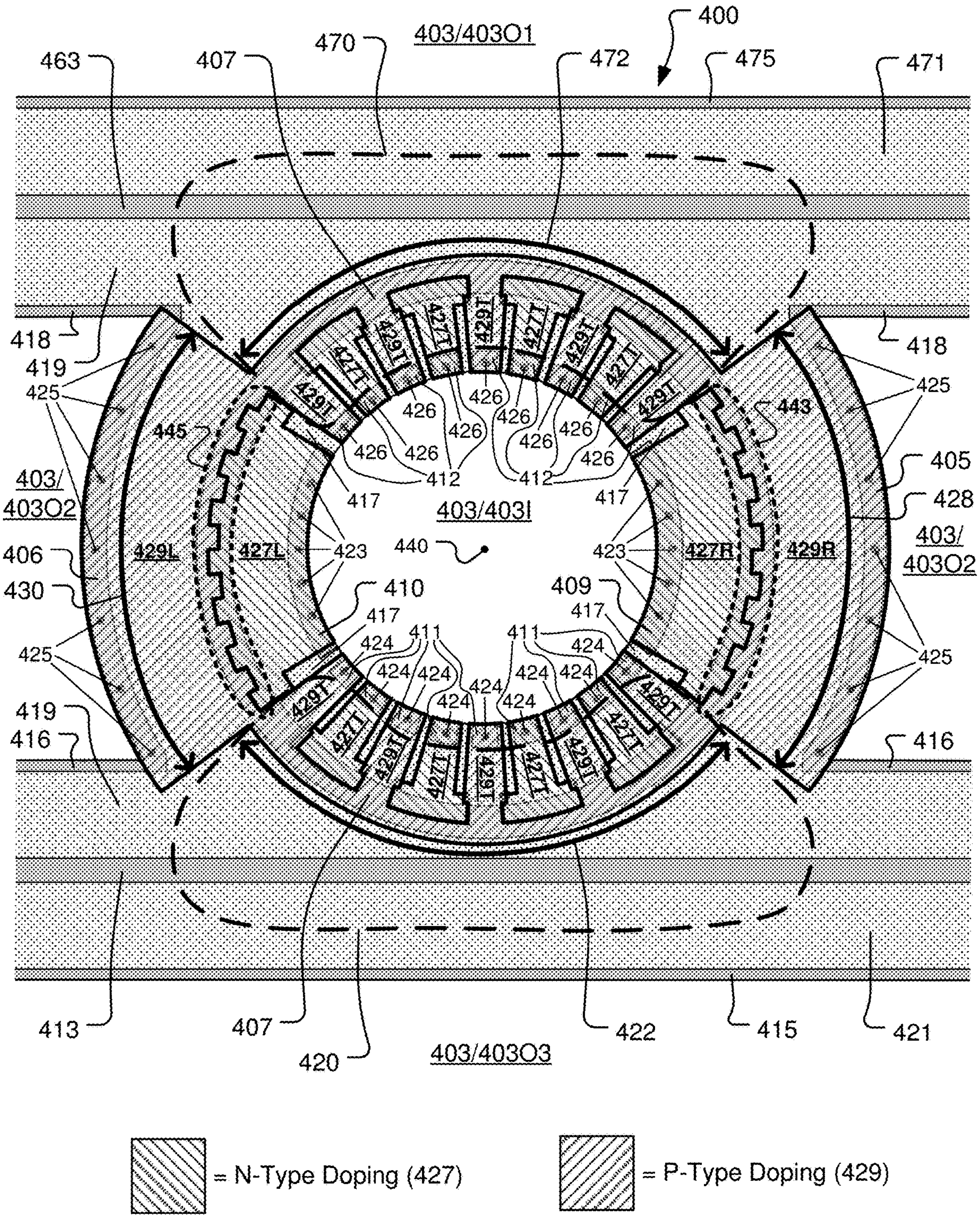

400
403/403O1
470
407
463
472
475
471
418
419
425
445
443
403/
403O2
406
430
429L
427L
423
440
403/403I
417
412
426
427T
429T
410
409
411
424
427R
429R
405
428
416
413
407
420
422
415
421
403/403O3
= N-Type Doping (427)
= P-Type Doping (429)

Fig. 4A

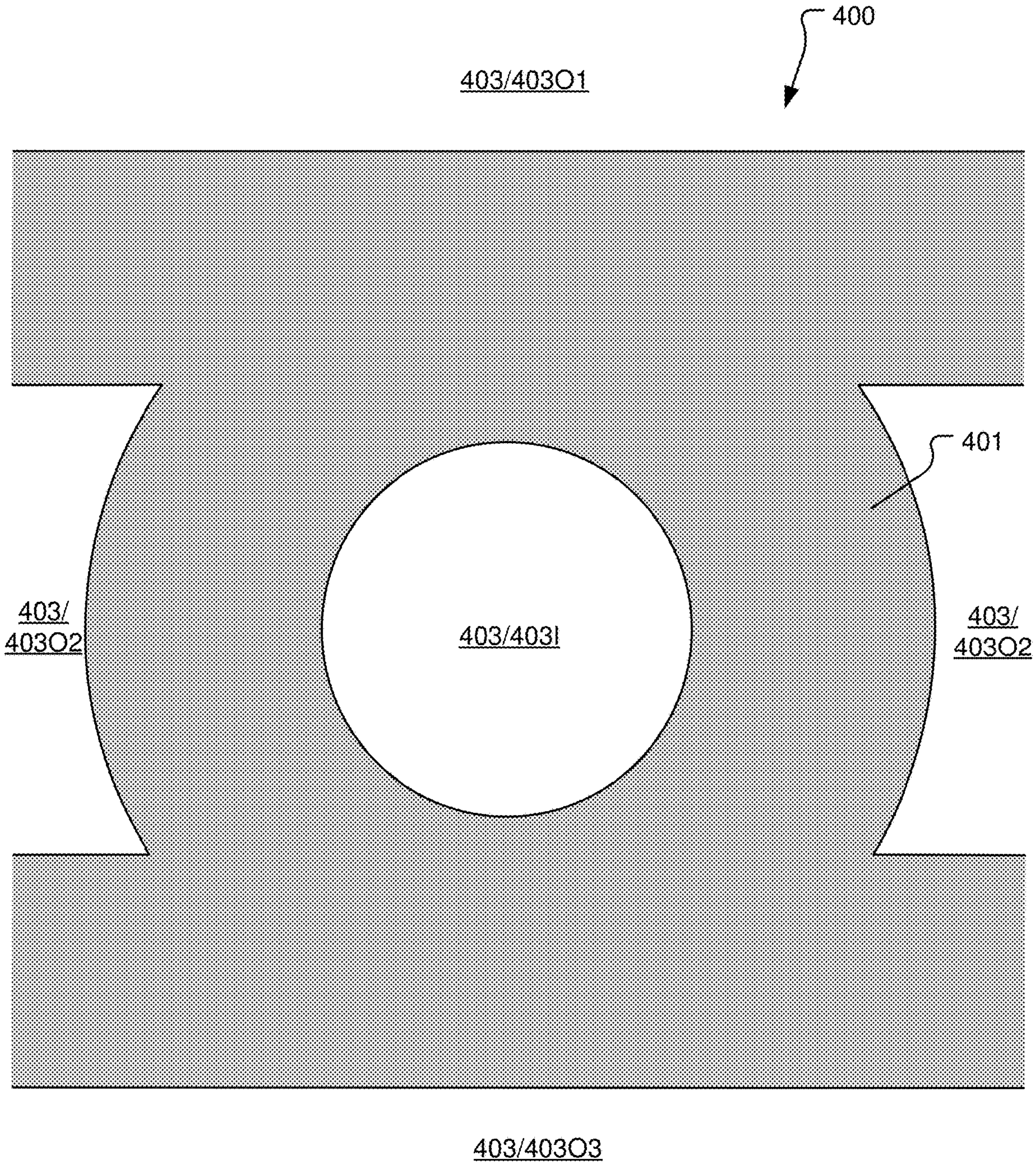


Fig. 4B

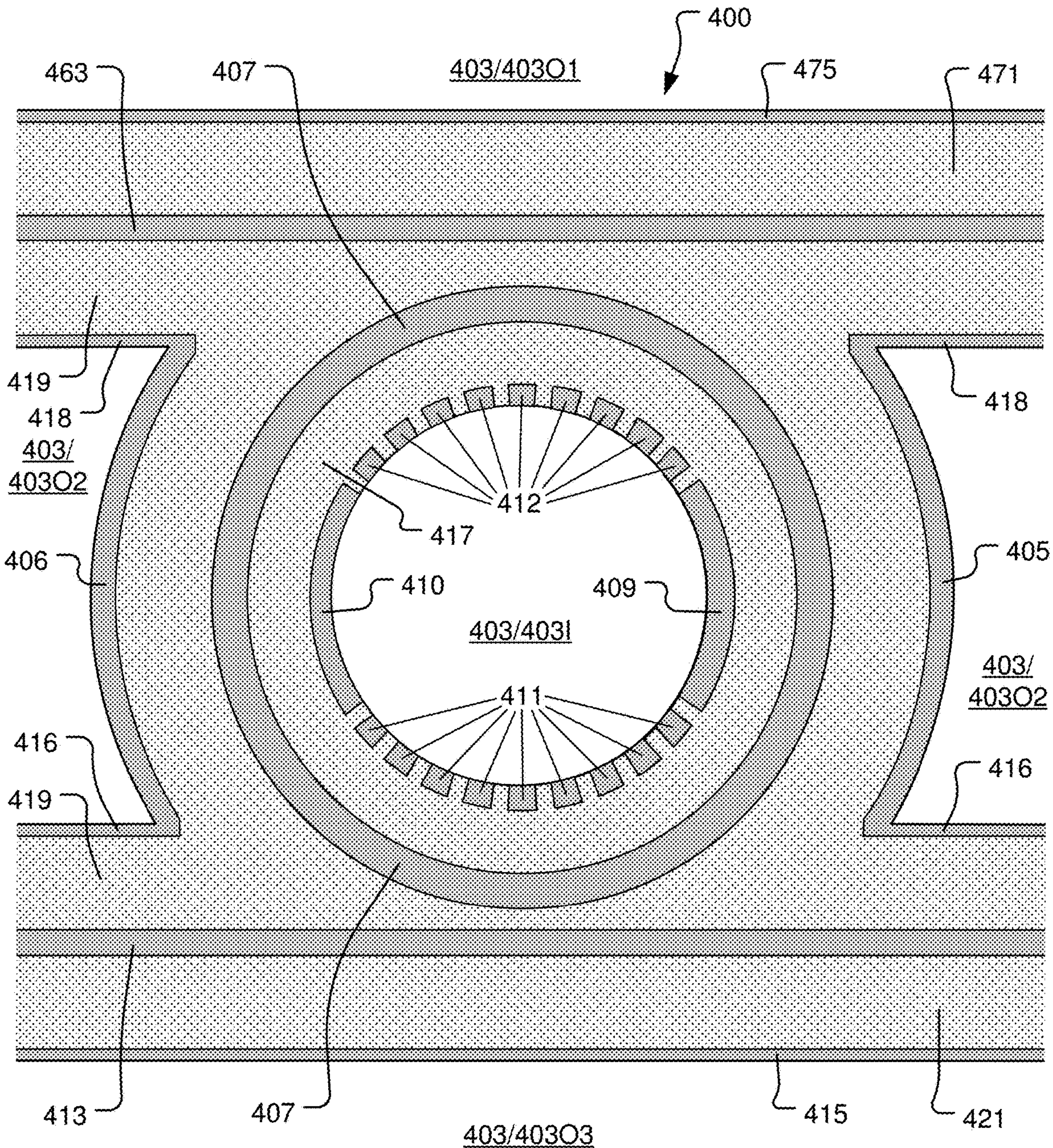
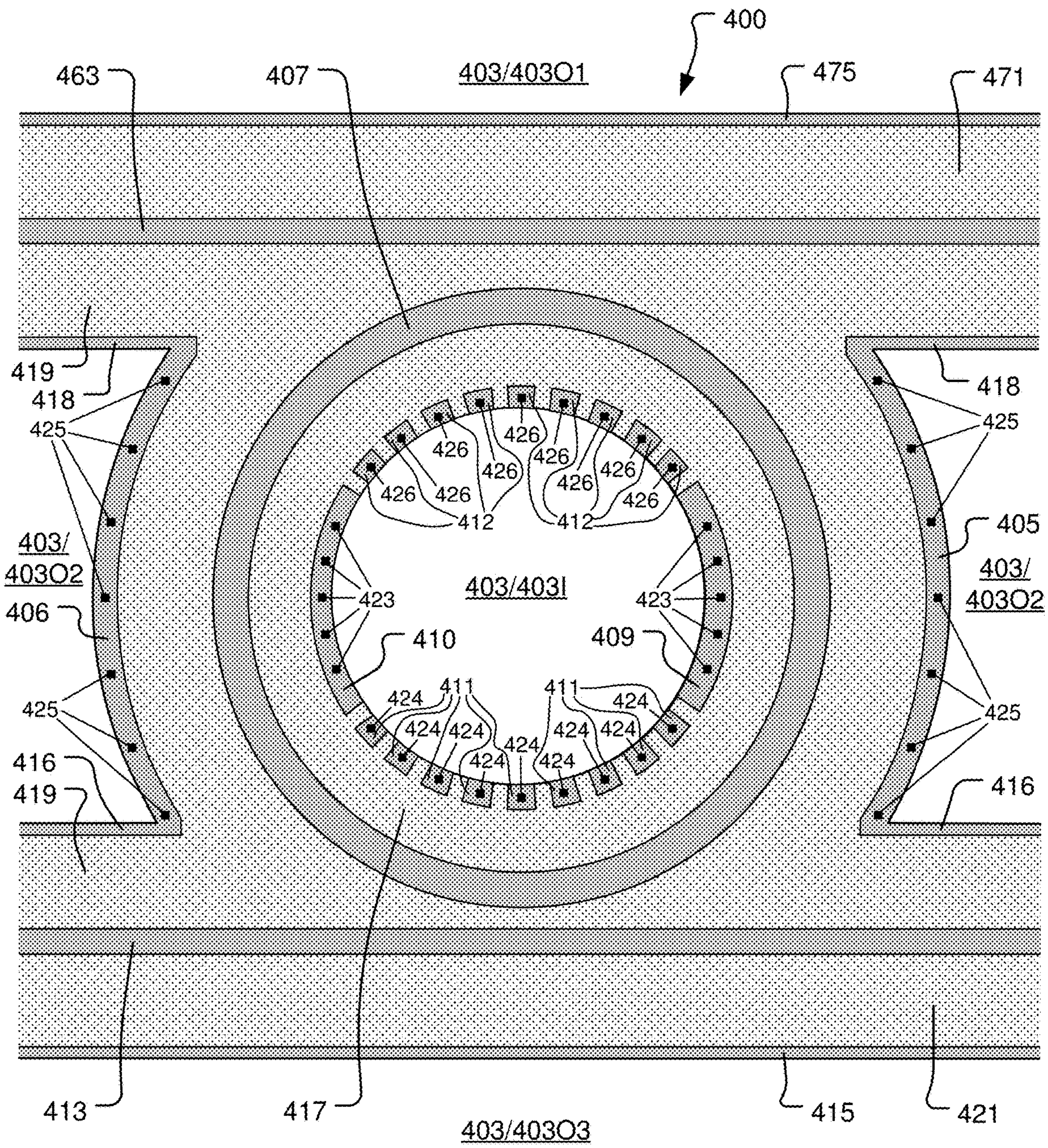

400
463
407
403/403O1
475
471
419
418
403/
403O2
412
417
406
410
409
405
403/403I
411
403/
403O2
416
419
416
418
413
407
415
421
403/403O3

Fig. 4C



400
403/403O1
463
407
475
471
419
418
425
403/
403O2
406
416
419
426
412
423
403/403I
410
409
411
424
418
425
405
403/
403O2
416
413
417
415
421
403/403O3

Fig. 4D

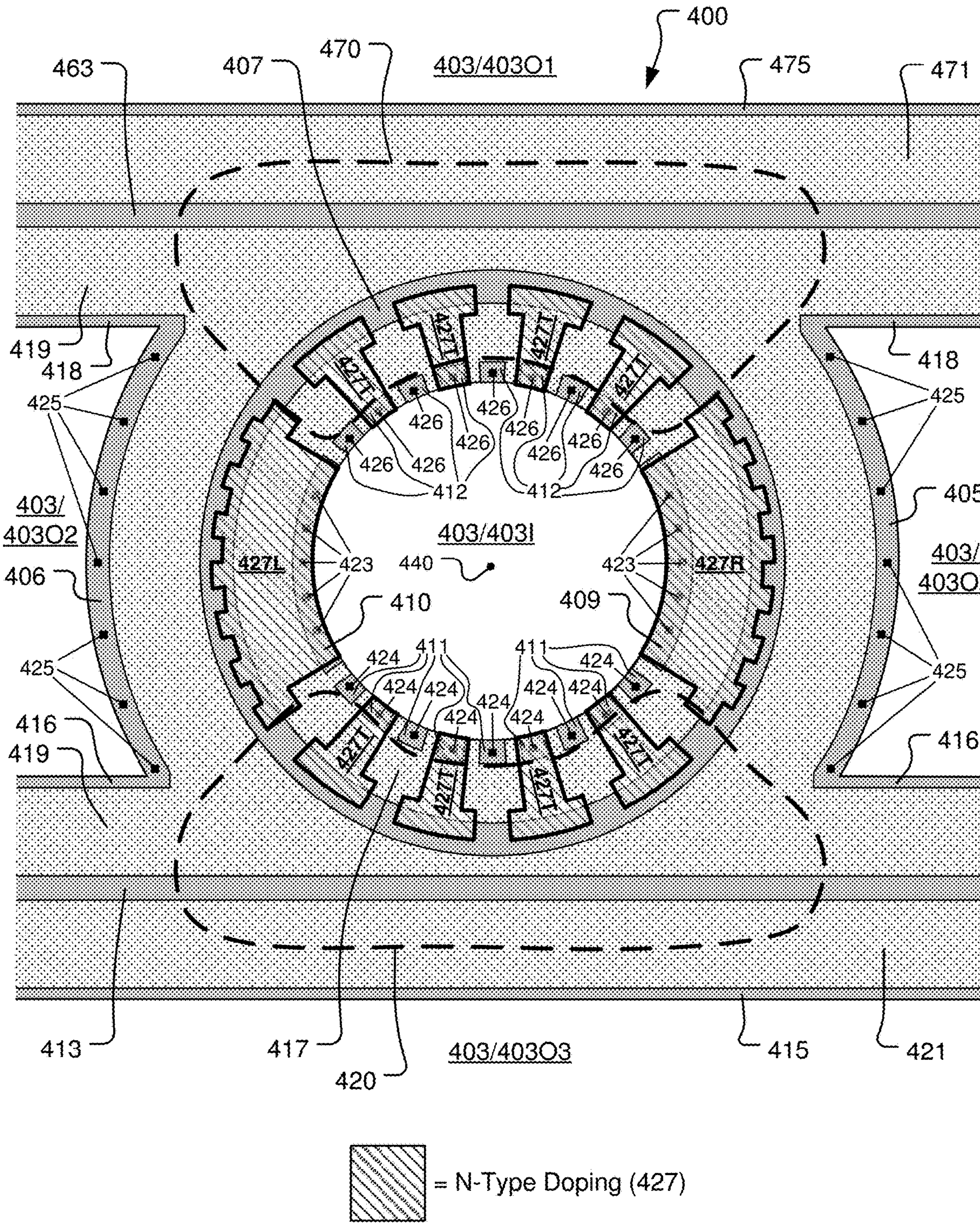

400
403/403O1
463
407
470
475
471
419
418
425
403/
403O2
406
416
419
427T
426
412
405
423
427L
427R
440
403/403I
410
409
411
424
413
417
420
403/403O3
415
421
= N-Type Doping (427)

Fig. 4E

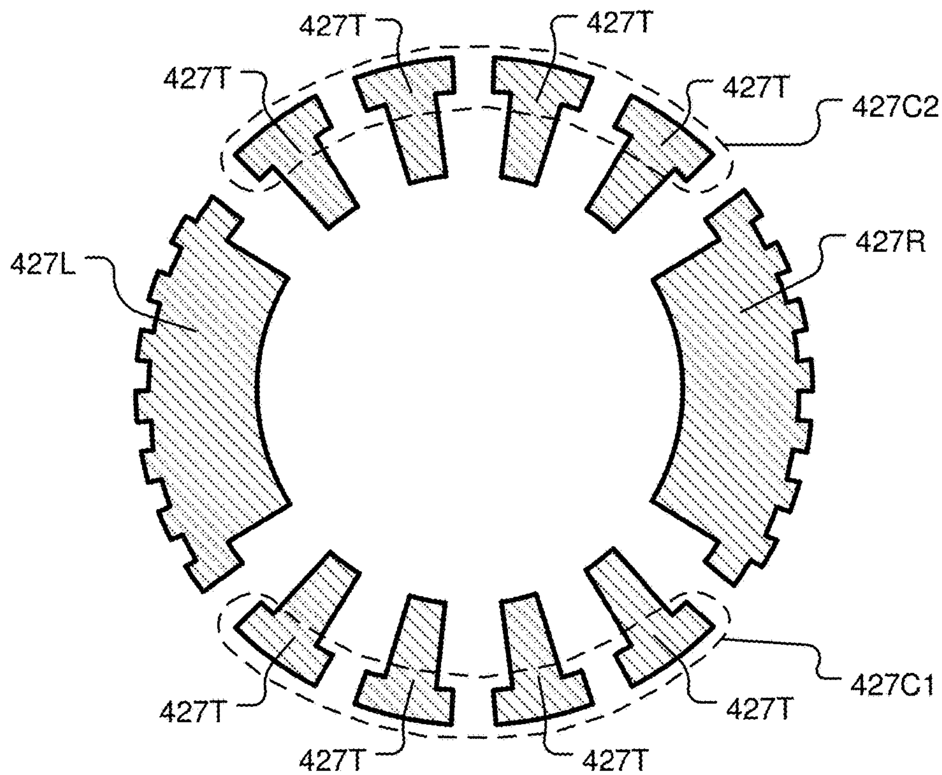

427T
427T
427T
427T
427C2
427L
427R
427T
427T
427T
427T
427C1

Fig. 4F

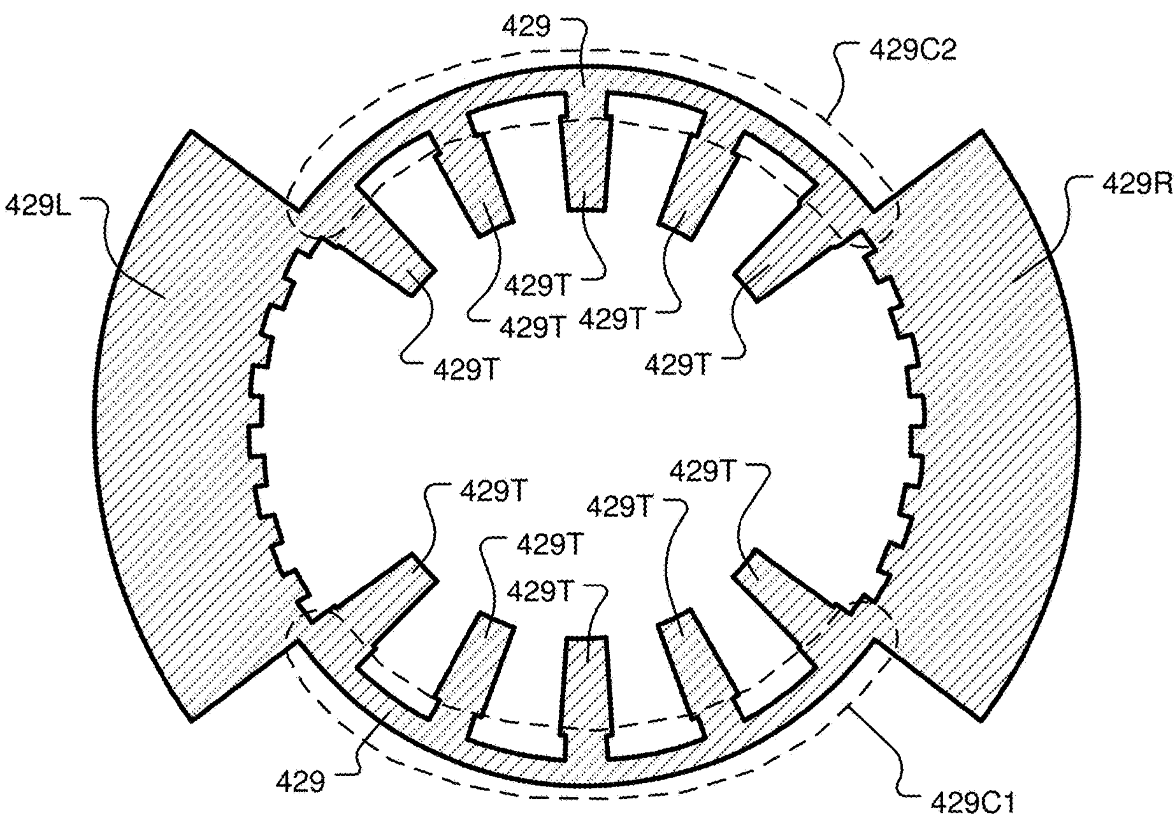

429
429C2
429L
429R
429T
429T
429T
429T
429T
429T
429T
429T
429T
429T
429T
429
429C1

Fig. 4G

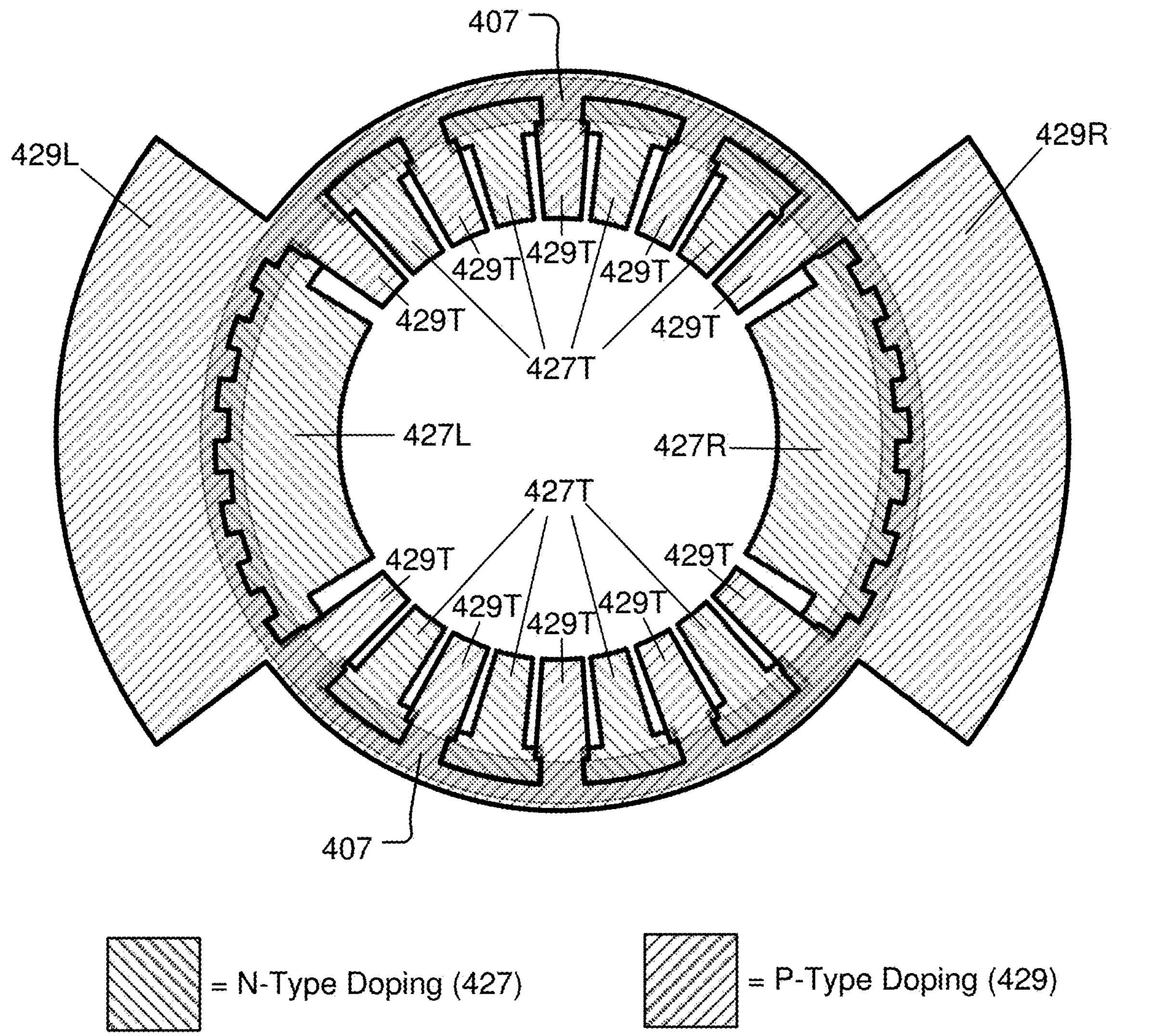

407
429L
429R
429T
429T
429T
429T
429T
429T
427T
427L
427R
427T
429T
429T
429T
429T
429T
429T
407
= N-Type Doping (427)
= P-Type Doping (429)

Fig. 4H

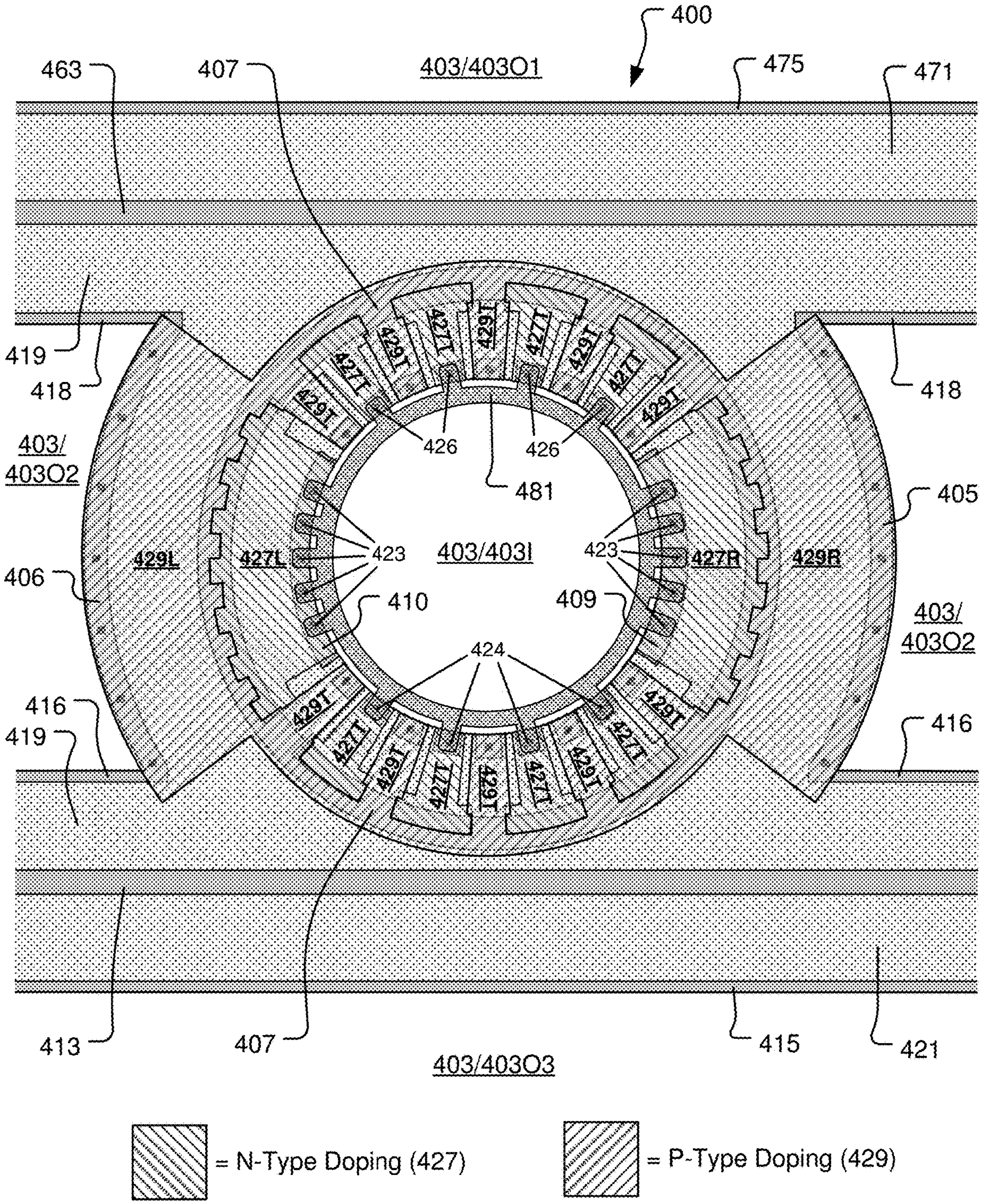

400
403/403O1
463
407
475
471
419
418
418
403/
403O2
426
426
481
405
429L
427L
423
403/403I
423
427R
429R
406
410
409
403/
403O2
424
429T
427T
416
419
416
413
407
415
421
403/403O3
= N-Type Doping (427)
= P-Type Doping (429)

Fig. 4I

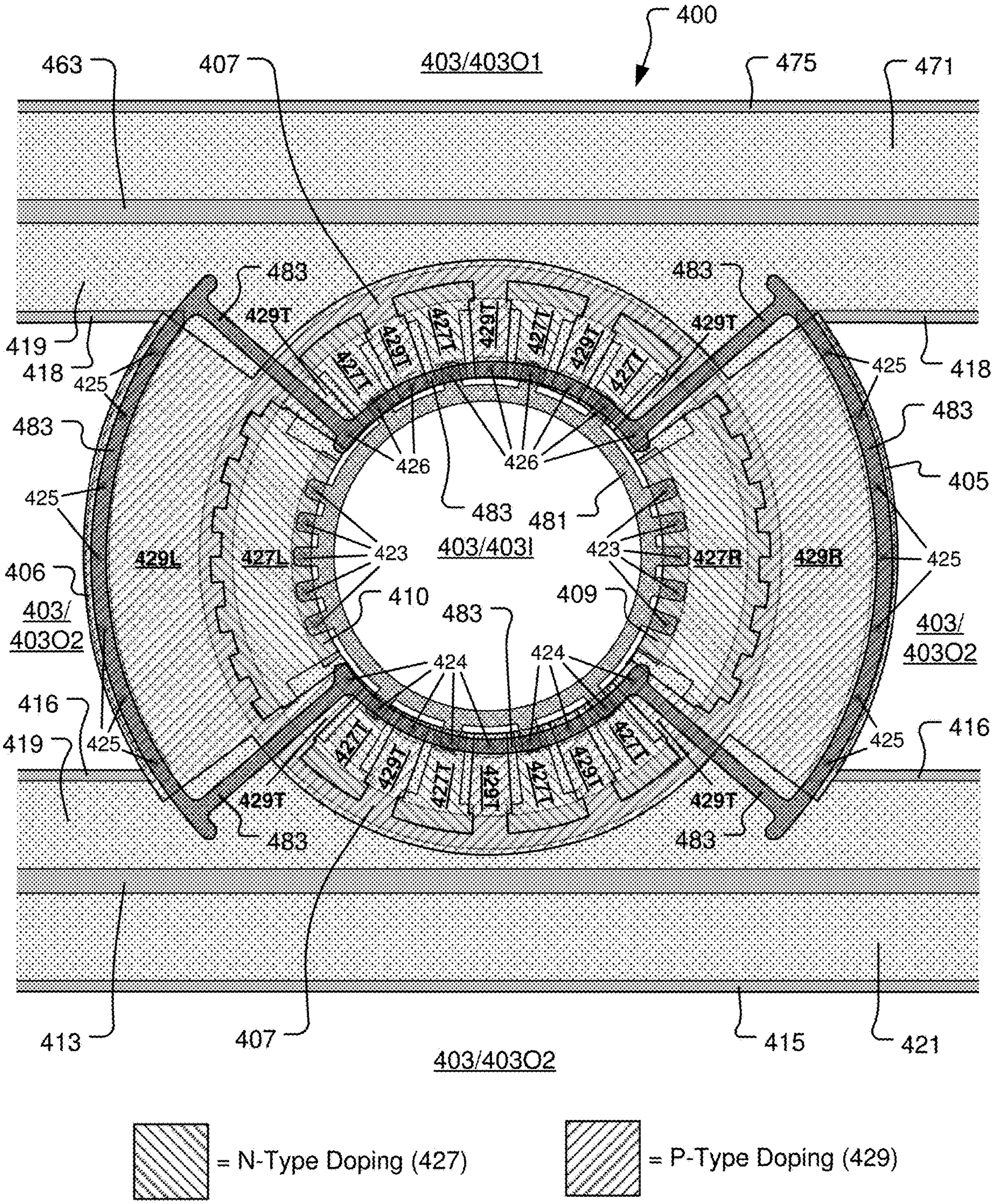

400
403/403O1
463
407
475
471
483
429T
427T
429T
427T
429T
427T
429T
427T
419
418
425
405
406
426
481
423
410
409
424
429L
427L
403/403I
427R
429R
403/
403O2
416
413
415
421
403/403O2
= N-Type Doping (427)
= P-Type Doping (429)

Fig. 4J

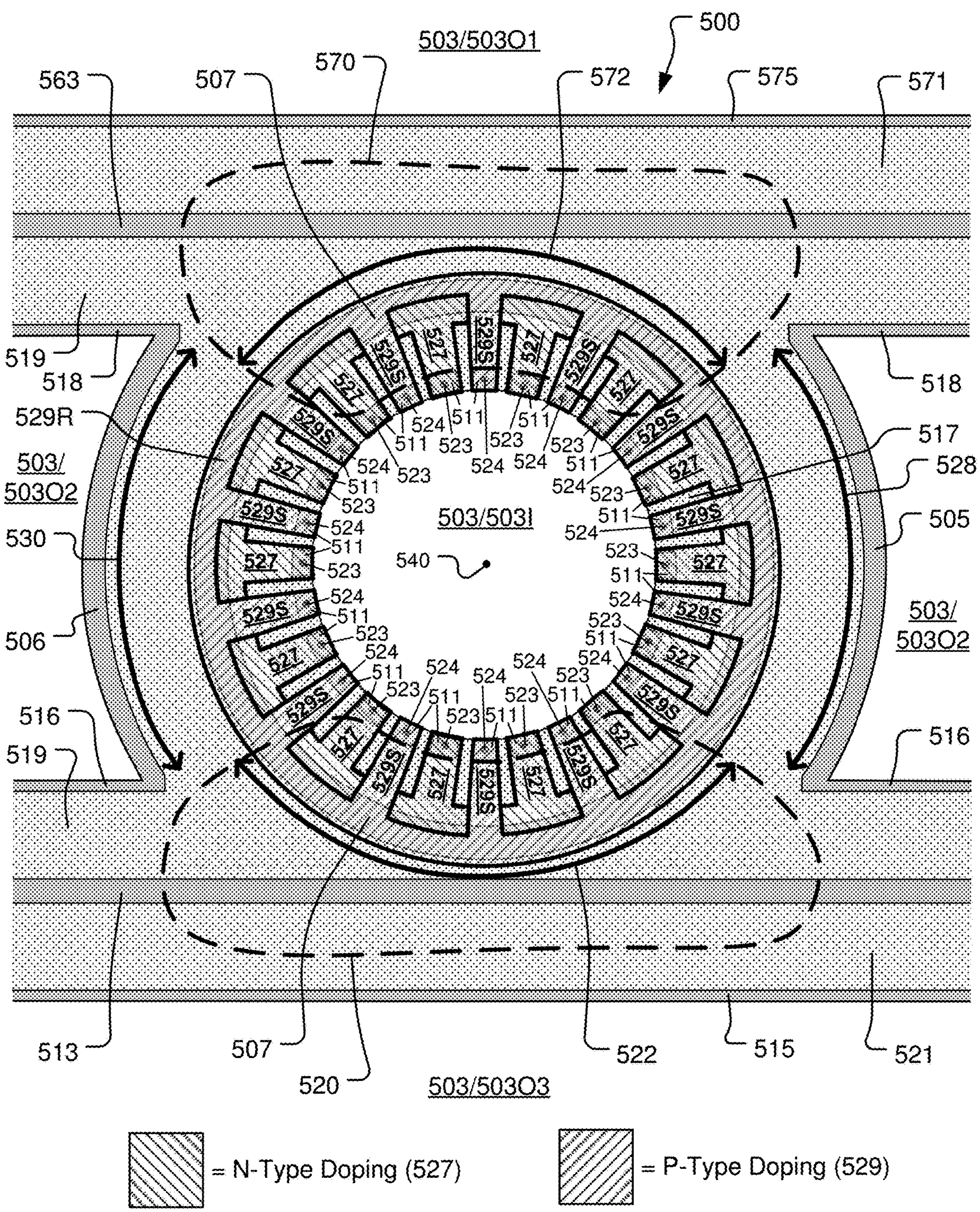

500
503/503O1
503/503O2
503/503I
503/503O3
505
506
507
511
513
515
516
517
518
519
520
521
522
523
524
527
528
529R
529S
530
540
563
570
571
572
575
= N-Type Doping (527)
= P-Type Doping (529)

Fig. 5A

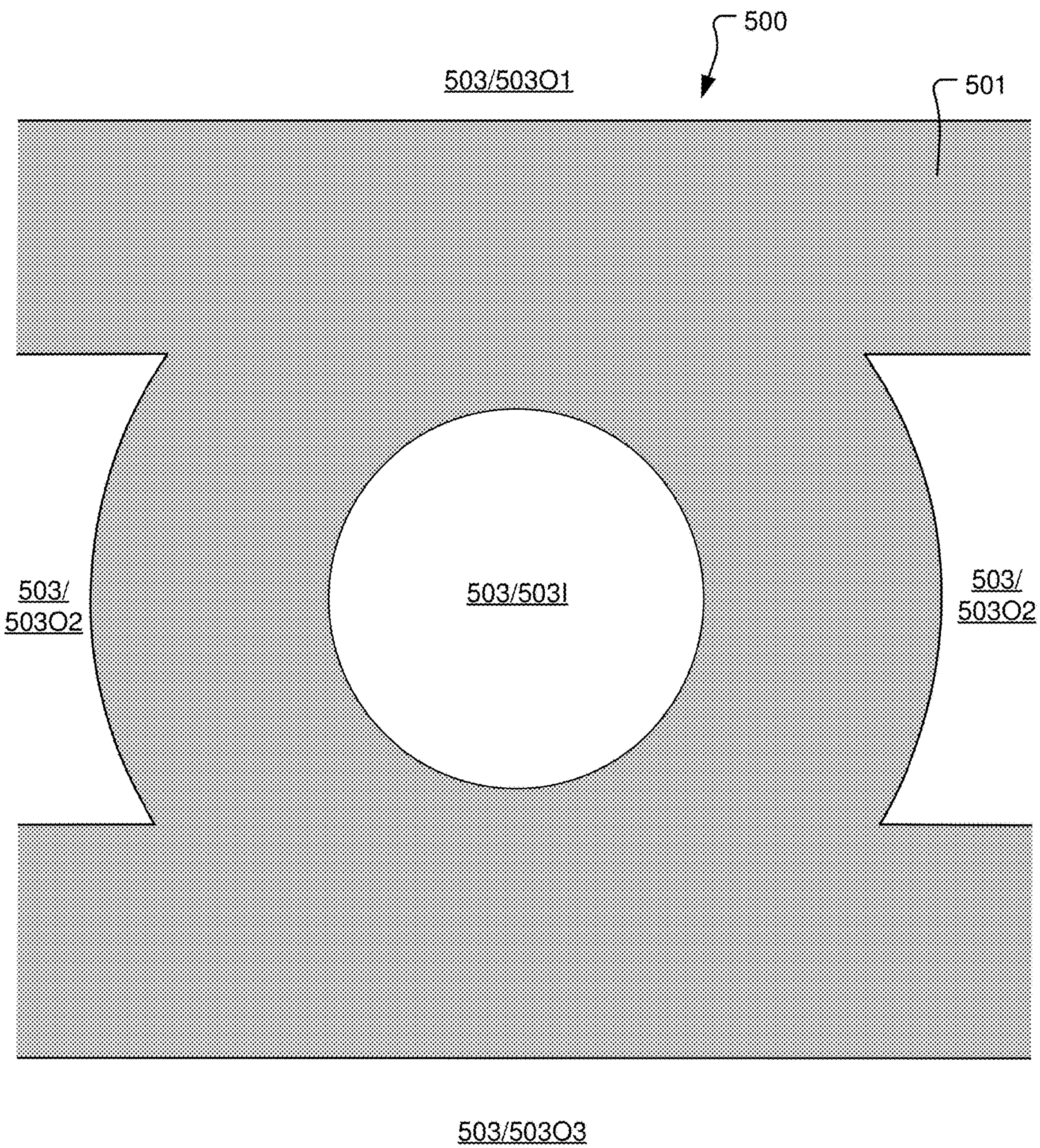


Fig. 5B

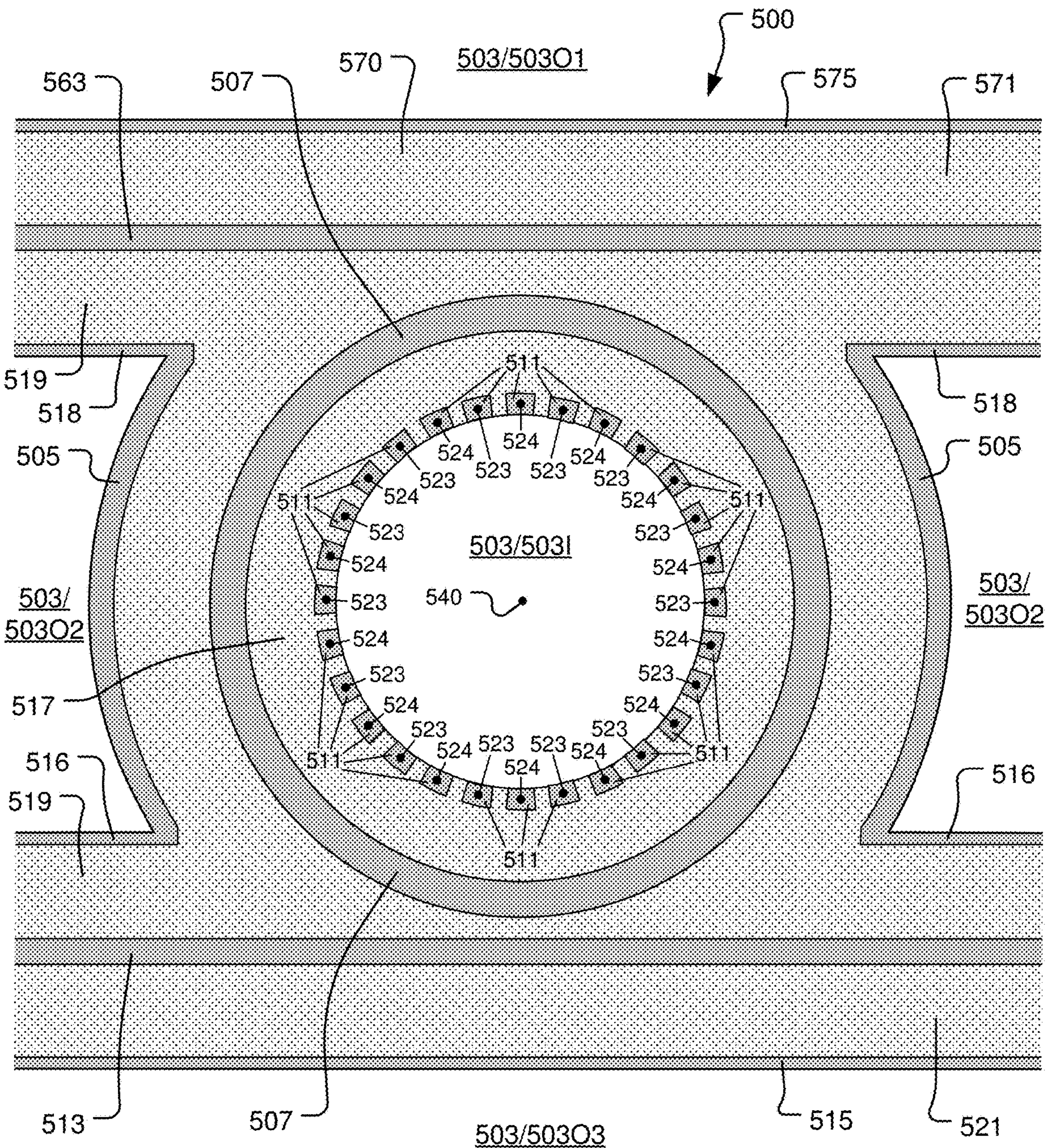
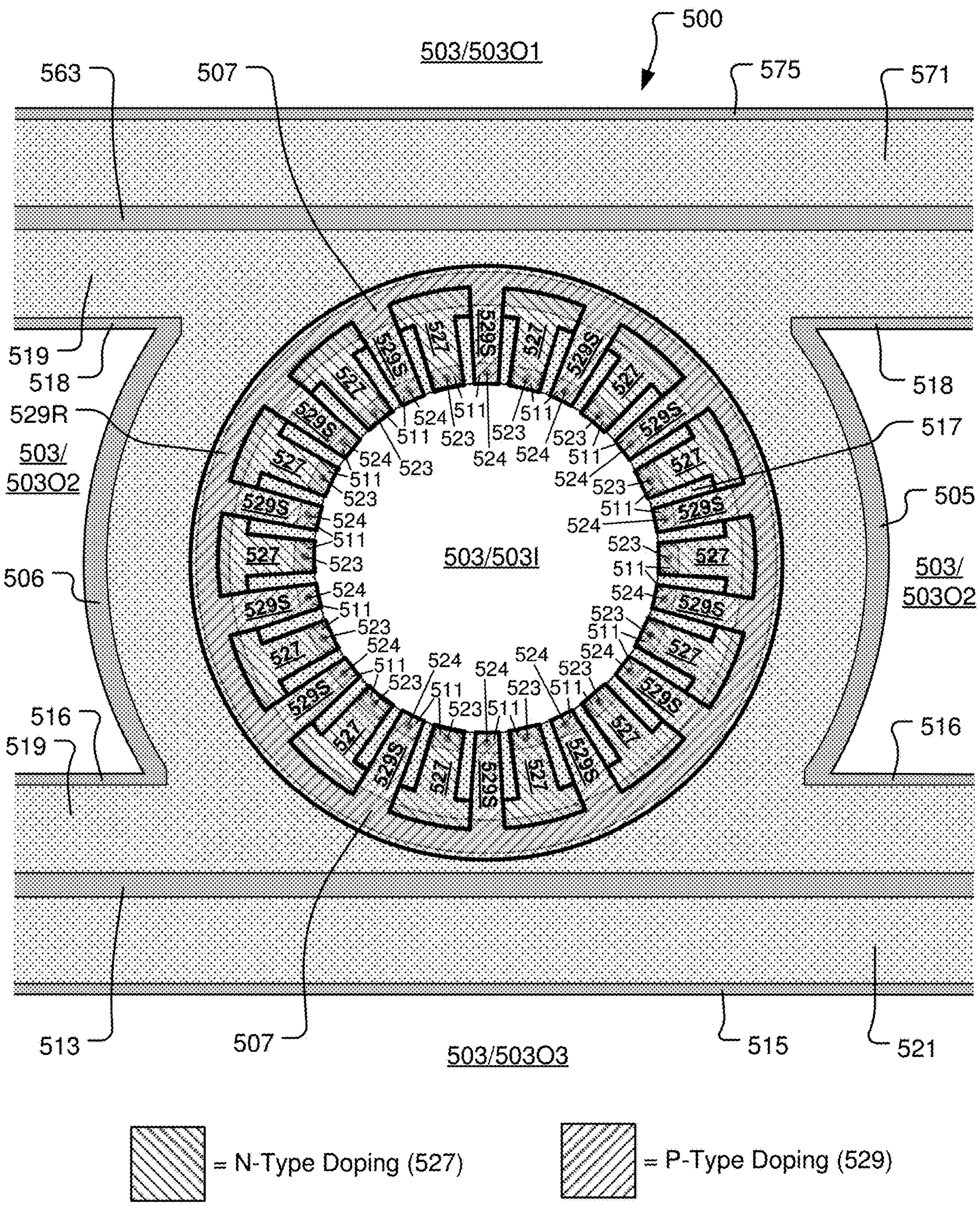

500
503/503O1
570
563
507
575
571
519
518
505
503/
503O2
517
516
511
524
523
503/503I
540
513
515
521
503/503O3

Fig. 5C



500
503/503O1
563
507
575
571
519
518
529R
503/
503O2
506
516
519
518
517
505
503/
503O2
516
503/503I
527
529S
511
523
524
513
507
515
521
503/503O3
= N-Type Doping (527)
= P-Type Doping (529)

Fig. 5D

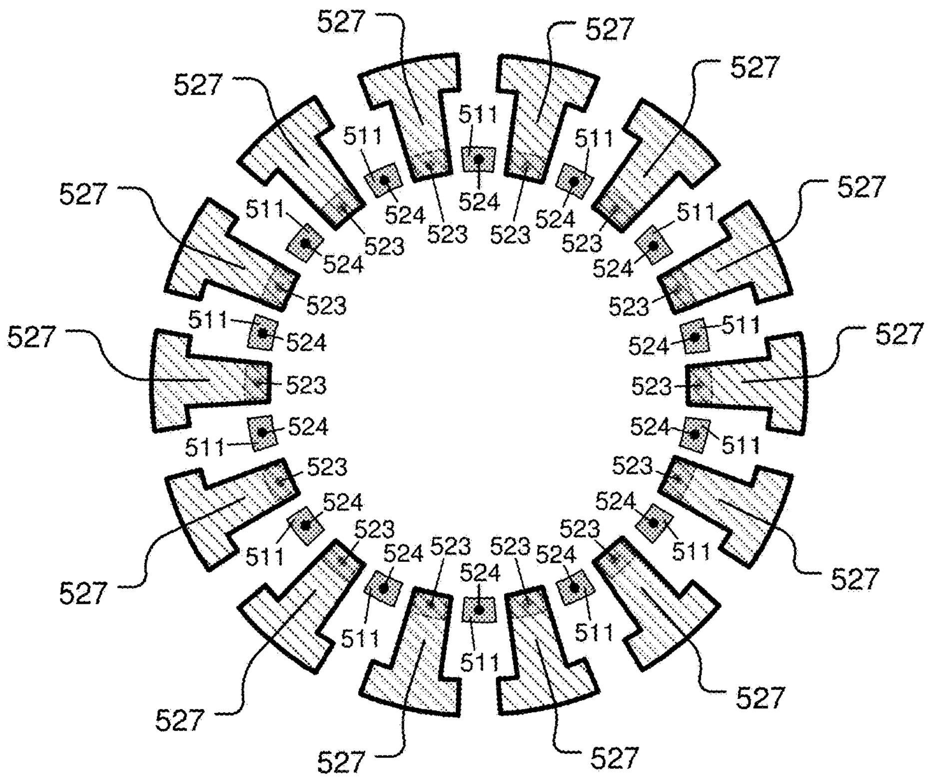


Fig. 5E

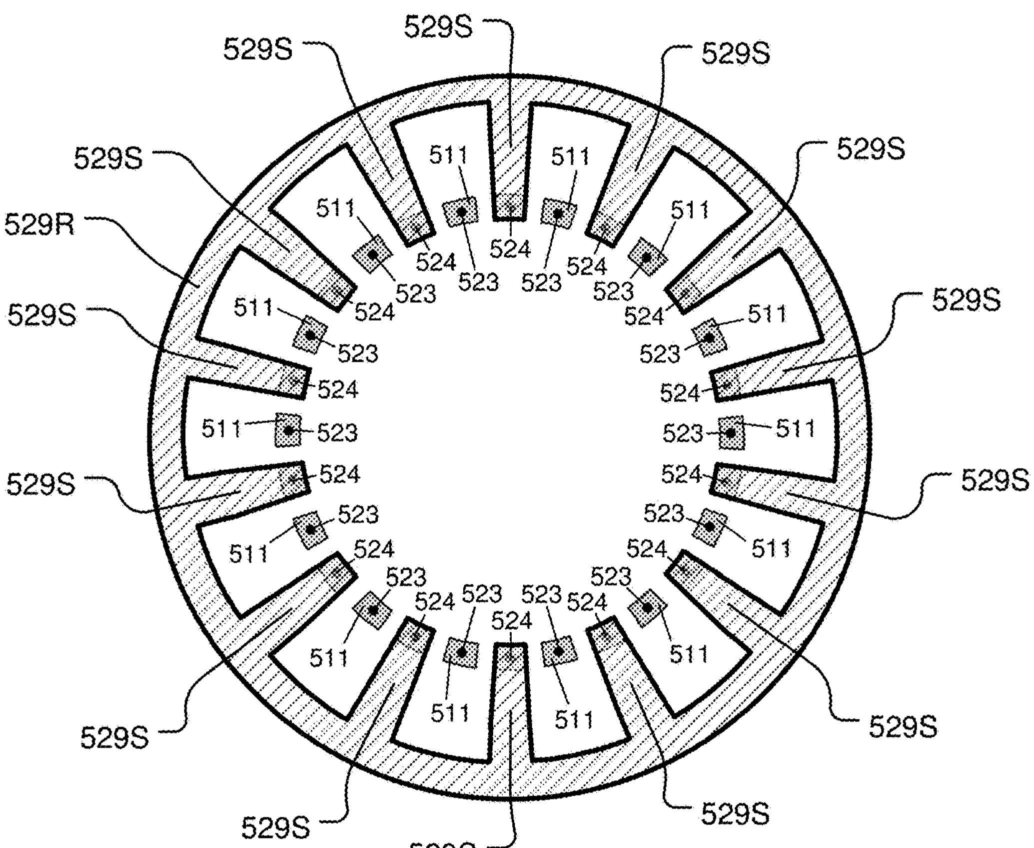
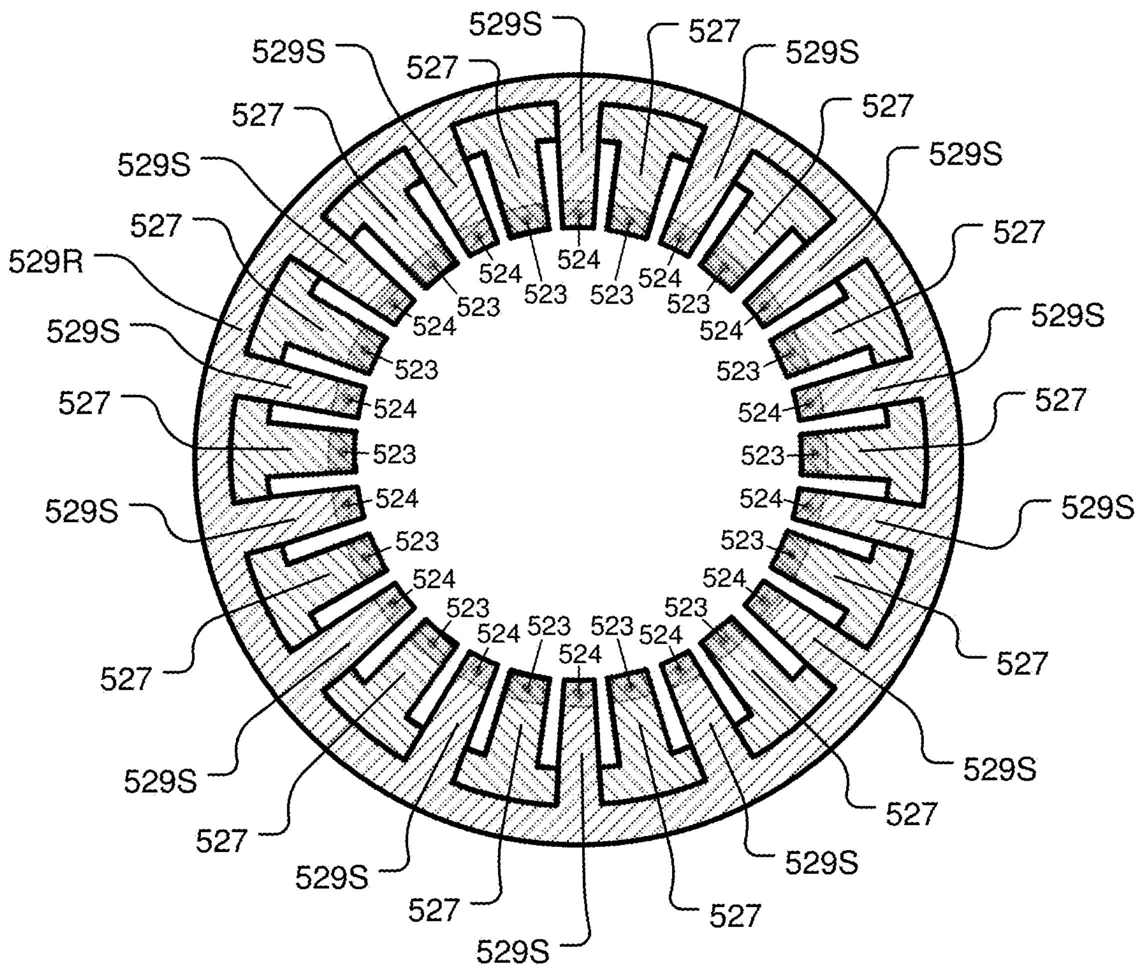


Fig. 5F


529S
527
529S
527
529S
527
529S
527
529R
529S
527
529S
527
529S
527
529S
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527
529S
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529S
527
529S
527
529S
527
529S
524
523

Fig. 5G

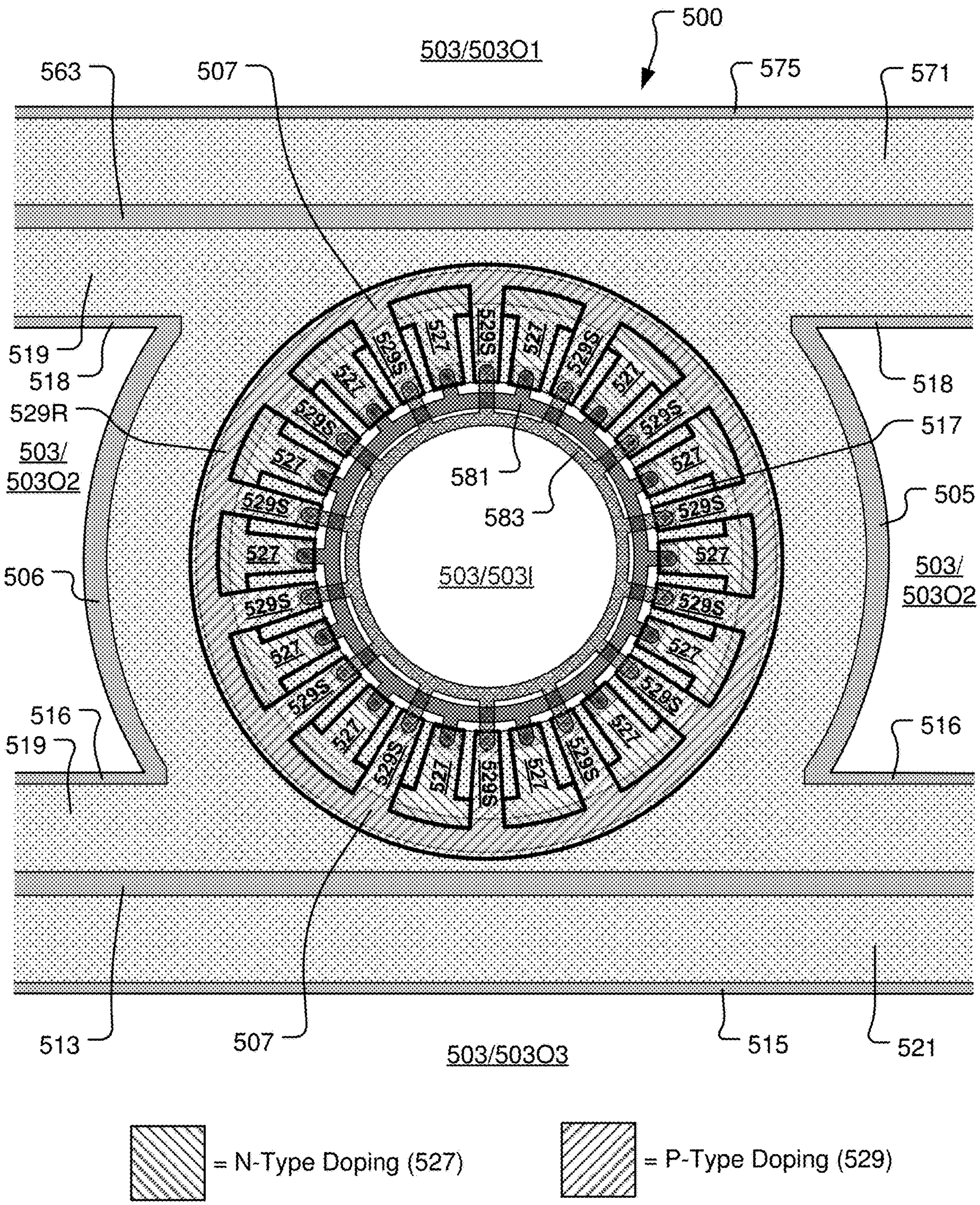
500
503/503O1
563
507
575
571
519
518
518
529R
517
503/
503O2
581
505
583
503/503I
503/
503O2
506
516
516
519
513
507
515
521
503/503O3
527
529S
= N-Type Doping (527)
= P-Type Doping (529)

Fig. 5H

RING MODULATOR WITH RIB RING OPTICAL WAVEGUIDE AND INTERDIGITATED PN JUNCTION DIODE

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] This application claims priority under 35 U.S.C. 119 (e) to U.S. Provisional Patent Application No. 63/554,935, filed on Feb. 16, 2024, the disclosure of which is incorporated herein by reference in its entirety for all purposes.

BACKGROUND OF THE INVENTION

[0002] Optical data communication systems operate by modulating laser light to encode digital data patterns within optical signals. The modulated laser light is transmitted through an optical data network from a sending node to a receiving node. The modulated laser light having arrived at the receiving node is de-modulated to obtain the original digital data patterns from the optical signals. The transmission of light through the optical data network includes transmission of light through optical fibers and transmission of light between optical fibers and photonic integrated circuits. In some embodiments, a photodiode is used to detect light of an optical data signal and convert the detected light into a photocurrent that can be processed through electrical circuitry to demodulate the optical data signal to obtain the original digital data pattern from the optical data signal. It is within this context that the present invention arises.

SUMMARY OF THE INVENTION

[0003] In an example embodiment, a photonic integrated circuit is disclosed. The photonic integrated circuit includes a first optical waveguide that has a ring shape. The first optical waveguide is formed of silicon and has a first vertical height. The photonic integrated circuit also includes an inner silicon region formed circumferentially along an inner side of the first optical waveguide. The inner silicon region has a second vertical height that is less than the first vertical height. The photonic integrated circuit also includes a second optical waveguide that is configured to semi-tangentially approach an outer side of the first optical waveguide and extend past the first optical waveguide at a first location, such that a first optical coupling region exists between a portion of the second optical waveguide and a first portion of the first optical waveguide about the first location. The photonic integrated circuit also includes a third optical waveguide that is configured to semi-tangentially approach the outer side of the first optical waveguide and extend past the first optical waveguide at a second location that is diametrically opposed to the first location with regard to the ring shape of the first optical waveguide, such that a second optical coupling region exists between a portion of the third optical waveguide and a second portion of the first optical waveguide about the second location. The photonic integrated circuit also includes an N-type doping region formed within the first optical waveguide and the inner silicon region. The N-type doping region includes a first set of multiple tab-shaped N-type doping regions formed within the first optical coupling region. The N-type doping region includes a second set of multiple tab-shaped N-type doping regions formed within the second optical coupling region. Each of the tab-shaped N-type doping regions in the first and second sets of multiple tab-shaped N-type doping regions is formed to project inward toward a center of the ring shape of the first optical waveguide. The photonic integrated circuit also includes a P-type doping region formed within the first optical waveguide and the inner silicon region. The P-type doping region includes a first set of multiple tab-shaped P-type doping regions formed within the first optical coupling region. The P-type doping region includes a second set of multiple tab-shaped P-type doping regions formed within the second optical coupling region. Each of the tab-shaped P-type doping regions in the first and second sets of multiple tab-shaped P-type doping regions is formed to project inward toward the center of the ring shape of the first optical waveguide. Positions of the first set of multiple tab-shaped N-type doping regions alternate with positions of the first set of multiple tab-shaped P-type doping regions along the first portion of the first optical waveguide, such that the first set of multiple tab-shaped N-type doping regions and the first set of multiple tab-shaped P-type doping regions collectively form a first interdigitated PN diode configuration within the first optical waveguide within the first optical coupling region. Positions of the second set of multiple tab-shaped N-type doping regions alternate with positions of the second set of multiple tab-shaped P-type doping regions along the second portion of the first optical waveguide, such that the second set of multiple tab-shaped N-type doping regions and the second set of multiple tab-shaped P-type doping regions collectively form a second interdigitated PN diode configuration within the first optical waveguide within the second optical coupling region.

[0004] In an example embodiment, a photonic integrated circuit is disclosed. The photonic integrated circuit includes a first optical waveguide that has a ring shape. The first optical waveguide is formed of silicon and has a first vertical height. The photonic integrated circuit also includes an inner silicon region formed circumferentially along an inner side of the first optical waveguide. The inner silicon region has a second vertical height that is less than the first vertical height. The photonic integrated circuit also includes a second optical waveguide that is configured to semi-tangentially approach an outer side of the first optical waveguide and extend past the first optical waveguide, such that an optical coupling region exists between a portion of the second optical waveguide and a portion of the first optical waveguide. The photonic integrated circuit also includes an N-type doping region formed within the first optical waveguide and the inner silicon region. The N-type doping region includes multiple tab-shaped N-type doping regions formed within the optical coupling region. Each of the multiple tab-shaped N-type doping regions is formed to project inward toward a center of the ring shape of the first optical waveguide. The photonic integrated circuit also includes a P-type doping region formed within the first optical waveguide and the inner silicon region. The P-type doping region includes multiple tab-shaped P-type doping regions formed within the optical coupling region. Each of the multiple tab-shaped P-type doping regions is formed to project inward toward the center of the ring shape of the first optical waveguide. Positions of the multiple tab-shaped N-type doping regions alternate with positions of the multiple tab-shaped P-type doping regions along the portion of the first optical waveguide within the optical coupling region, such that the multiple tab-shaped N-type doping regions and the multiple tab-shaped P-type doping regions collectively form an interdigitated PN diode configuration within the first optical waveguide within the optical coupling region.

[0005] In an example embodiment, a photonic integrated circuit is disclosed. The photonic integrated circuit includes a first optical waveguide that has a ring shape. The first optical waveguide is formed of silicon and has a first vertical height. The photonic integrated circuit also includes an inner silicon region formed circumferentially along an inner side of the first optical waveguide. The inner silicon region has a second vertical height that is less than the first vertical height. The photonic integrated circuit also includes a second optical waveguide that is configured to semi-tangentially approach an outer side of the first optical waveguide and extend past the first optical waveguide at a first location, such that a first optical coupling region exists between a portion of the second optical waveguide and a first portion of the first optical waveguide about the first location. The photonic integrated circuit also includes a third optical waveguide that is configured to semi-tangentially approach the outer side of the first optical waveguide and extend past the first optical waveguide at a second location that is diametrically opposed to the first location with regard to the ring shape of the first optical waveguide, such that a second optical coupling region exists between a portion of the third optical waveguide and a second portion of the first optical waveguide about the second location. The photonic integrated circuit also includes an N-type doping region formed within the first optical waveguide and the inner silicon region. The N-type doping region includes multiple tab-shaped N-type doping regions formed within the first optical waveguide and the inner silicon region. The multiple tab-shaped N-type doping regions are positioned in a spaced apart manner along a full circumferential path of the ring shape of the first optical waveguide. Each of the multiple tab-shaped N-type doping regions is formed to project inward toward a center of the ring shape of the first optical waveguide. The photonic integrated circuit also includes a P-type doping region formed within the first optical waveguide and the inner silicon region. The P-type doping region includes multiple tab-shaped P-type doping regions formed within the first optical waveguide and the inner silicon region. Each of the multiple tab-shaped P-type doping regions is positioned between a different pair of the multiple tab-shaped N-type doping regions along the full circumferential path of the ring shape of the first optical waveguide. Each of the multiple tab-shaped P-type doping regions is formed to project inward toward the center of the ring shape of the first optical waveguide. The multiple tab-shaped N-type doping regions and the multiple tab-shaped P-type doping regions collectively form an interdigitated PN diode configuration within the first optical waveguide along the full circumferential path of the ring shape of the first optical waveguide. A first portion of the interdigitated PN diode configuration is positioned within the first optical coupling region. A second portion of the interdigitated PN diode configuration is positioned within the second optical coupling region. A third portion of the interdigitated PN diode configuration is positioned between the first optical coupling region and the second optical coupling region on a first side of the center of the ring shape of the first optical waveguide. A fourth portion of the interdigitated PN diode configuration is positioned between the first optical coupling region and the second optical coupling region on a second side of the center of the ring shape of the first optical waveguide.

BRIEF DESCRIPTION OF THE DRAWINGS

[0006] FIG. **1**A shows a top view of an example ring modulator that implements a rib ring, in accordance with some embodiments.

[0007] FIG. **1**B shows a vertical cross-section through the rib ring and the optical waveguide at a location of their closest approach to each other, referenced as View A-A in FIG. **1**A, in accordance with some embodiments.

[0008] FIG. **1**C shows a vertical cross-section through the rib ring and the full-height (full-thickness) silicon regions, referenced as View B-B in FIG. **1**A, in accordance with some embodiments.

[0009] FIG. **1**D shows a top view of a configuration of full-height (full-thickness) silicon formed within the cladding material, in accordance with some embodiments.

[0010] FIG. **1**E shows a top view of the configuration of full-height (full-thickness) silicon with portions of the full-height (full-thickness) silicon etched away to form the partial-height (partial-thickness) silicon regions, in accordance with some embodiments.

[0011] FIG. **1**F shows a top view of the partially formed ring modulator of FIG. **1**E with formation of the inner electrical contacts and the outer electrical contacts, in accordance with some embodiments.

[0012] FIG. **1**G shows a top view of the partially formed ring modulator of FIG. **1**F with the N-type doping region formed, in accordance with some embodiments.

[0013] FIG. **2**A shows the top view of the partially formed ring modulator of FIG. **1**F with annotations for computation of the optical coupling length of the rib ring along which the lateral PN junction diode is excluded, in accordance with some embodiments.

[0014] FIG. **2**B shows a top view of a partially formed ring modulator that has a second optical waveguide and a second optical coupling region, in accordance with some embodiments.

[0015] FIG. **3**A shows a top view of a ring modulator that implements an interdigitated diode configuration within an optical coupling region between an optical waveguide and a rib ring of the ring modulator in order to optimize modulation efficiency while minimizing optical loss in the optical waveguide, in accordance with some embodiments.

[0016] FIG. **3**B shows a vertical cross-section through the rib ring and the optical waveguide at a location of their closest approach to each other, referenced as View A-A in FIG. **3**A, in accordance with some embodiments.

[0017] FIG. **3**C shows a vertical cross-section through the rib ring and the full-height (full-thickness) silicon regions, referenced as View B-B in FIG. **3**A, in accordance with some embodiments.

[0018] FIG. **3**D shows a top view of a configuration of full-height (full-thickness) silicon formed within the cladding material, in accordance with some embodiments.

[0019] FIG. **3**E shows a top view of the configuration of full-height (full-thickness) silicon of FIG. **3**D with portions of the full-height (full-thickness) silicon etched away to form the partial-height (partial-thickness) silicon regions, in accordance with some embodiments.

[0020] FIG. **3**F shows a top view of the partially formed ring modulator of FIG. **3**E with formation of the inner electrical contacts, the inner electrical contacts, and the outer electrical contacts, in accordance with some embodiments.

[0021] FIG. **3**G shows a top view of the partially formed ring modulator of FIG. **3**F with formation of the N-type doping region and the tab-shaped N-type doping regions, in accordance with some embodiments.

[0022] FIG. **3**H shows an isolated top view of the N-type doping region and the tab-shaped N-type doping regions, in accordance with some embodiments.

[0023] FIG. **3**I shows an isolated top view of the P-type doping region and the tab-shaped P-type doping regions, in accordance with some embodiments.

[0024] FIG. **3**J shows an isolated top view of the P-type doping region and the tab-shaped P-type doping regions positioned in relation with the N-type doping region and the tab-shaped N-type doping regions, in accordance with some embodiments.

[0025] FIG. **4**A shows a top view of a ring modulator that implements a first interdigitated diode configuration within a first optical coupling region and that implements a second interdigitated diode configuration within a second optical coupling region, in accordance with some embodiments.

[0026] FIG. **4**B shows a top view of a configuration of full-height (full-thickness) silicon formed within the cladding material, in accordance with some embodiments.

[0027] FIG. **4**C shows a top view of the configuration of full-height (full-thickness) silicon with portions of the full-height (full-thickness) silicon etched away to form the partial-height (partial-thickness) silicon regions, in accordance with some embodiments.

[0028] FIG. **4**D shows a top view of the partially formed ring modulator of FIG. **4**C with formation of the inner electrical contacts, the inner electrical contacts, the inner electrical contacts, and the outer electrical contacts, in accordance with some embodiments.

[0029] FIG. **4**E shows a top view of the partially formed ring modulator of FIG. **4**D with formation of the N-type doping regions and the tab-shaped N-type doping regions, in accordance with some embodiments.

[0030] FIG. **4**F shows an isolated top view of the N-type doping regions and the tab-shaped N-type doping regions, in accordance with some embodiments.

[0031] FIG. **4**G shows an isolated top view of the P-type doping regions and the tab-shaped P-type doping regions, in accordance with some embodiments.

[0032] FIG. **4**H shows an isolated top view of the P-type doping regions and the tab-shaped P-type doping regions positioned in relation with the N-type doping regions and the tab-shaped N-type doping regions, in accordance with some embodiments.

[0033] FIG. **4**I shows a top view of the ring modulator with the N-type doping regions and the tab-shaped N-type doping regions electrically connected to a first electrical node by way of an electrical conductor, in accordance with some embodiments.

[0034] FIG. **4**J shows a top view of the ring modulator of FIG. **4**I with the P-type doping regions and the tab-shaped P-type doping regions electrically connected to a second electrical node by way of an electrical conductor, in accordance with some embodiments.

[0035] FIG. **5**A shows a top view of a ring modulator that implements a circuitous interdigitated diode configuration that extends through both a first optical coupling region and a second optical coupling region, in accordance with some embodiments.

[0036] FIG. **5**B shows a top view of a configuration of full-height (full-thickness) silicon formed within the cladding material, in accordance with some embodiments.

[0037] FIG. **5**C shows a top view of the configuration of full-height (full-thickness) silicon with portions of the full-height (full-thickness) silicon etched away to form the partial-height (partial-thickness) silicon regions, in accordance with some embodiments.

[0038] FIG. **5**D shows a top view of the partially formed ring modulator of FIG. **5**C having the N-type doping region and the P-type doping region formed thereon, in accordance with some embodiments.

[0039] FIG. **5**E shows an isolated top view of the N-type doping regions, in accordance with some embodiments.

[0040] FIG. **5**F shows an isolated top view of the P-type doping region, including the P-type doped outer rim region and multiple P-type doped spoke regions, in accordance with some embodiments.

[0041] FIG. **5**G shows an isolated view of the N-type doping regions and the P-type doping region positioned relative to each other as in the ring modulator, in accordance with some embodiments.

[0042] FIG. **5**H shows the top view of the ring modulator of FIG. **5**D with the N-type doping regions electrically connected to a first electrical node by way of an electrical conductor, in accordance with some embodiments.

DETAILED DESCRIPTION

[0043] In the following description, numerous specific details are set forth in order to provide an understanding of the embodiments disclosed herein. It will be apparent, however, to one skilled in the art that the embodiments disclosed herein may be practiced without some or all of these specific details. In other instances, well known process operations have not been described in detail in order not to unnecessarily obscure the disclosed embodiments.

[0044] The embodiments disclosed herein relate to optical data communication. Optical data communication systems operate by modulating laser light to encode digital data patterns within optical signals. In some embodiments, a ring modulator is used to modulate continuous wave laser light to generate the modulated laser light that conveys the encoding of digital data patterns. In some embodiments, the ring modulator is positioned within an evanescent optically coupling distance from a bus optical waveguide and operates to modulate light that is propagating through the bus optical waveguide. The modulated laser light is transmitted through an optical data network from a sending node to a receiving node. The modulated laser light having arrived at the receiving node is de-modulated to obtain the original digital data patterns from the optical signals. The transmission of light through the optical data network includes transmission of light through optical fibers and transmission of light between optical fibers and photonic integrated circuits. In some embodiments, a photodiode is used to detect light of an optical data signal and convert the detected light into a photocurrent that can be processed through electrical circuitry to demodulate the optical data signal to obtain the original digital data pattern from the optical data signal.

[0045] Optical cavities are used in a variety of applications in optical data communication systems, such as in lasers, optical modulators, optical splitters, optical routers, optical switches, and optical detectors, among other applications. In various applications and configurations, optical cavities may show strong wavelength selectivity. For this reason, optical cavities are useful in systems that rely on multiple optical signals transmitting information at different wavelengths. In some embodiments, optical cavities are configured as ring resonators and/or disk resonators to enable applications in which light that is coupled from an input optical waveguide into the optical cavity of the ring/disk resonator is either efficiently routed to a separate output optical waveguide, or absorbed within the optical cavity of the ring/disk resonator at specific wavelengths. Also, optical cavities, such as ring/disk resonators, are useful in sensing applications, such as in biological or chemical sensing applications in which a high concentration of optical power is needed in a small area.

[0046] The term "waveguide" as used herein refers to an optical waveguide structure through which light is guided. The term "ring resonator" as used herein refers to a circuitous (ring) shaped optical waveguide structure through which light is guided. The term "ring modulator" as used herein refers to a circuitous (ring) shaped optical waveguide structure through which light is guided and within which a light signal is modulated, such as to encode digital data within the modulated light signal. The term "bus waveguide" as used herein refers to an optical waveguide structure through which light is guided that is positioned next to (within an evanescent optical coupling distance of) another waveguide, such as a ring resonator or ring modulator. In some embodiments, the bus waveguide is configured to convey input light to a ring resonator/modulator and convey transmitted/modulated light away from the ring resonator/modulator. The term "drop waveguide" as used herein refers to an optical waveguide structure through which light is guided that is positioned next to (within an evanescent optical coupling distance of) another waveguide, such as a ring resonator or ring modulator. In some embodiments, the drop waveguide is configured to convey transmitted/modulated light away from a ring resonator/modulator.

[0047] Since the bandgap energy of silicon is larger than that of photons at telecom frequencies, optical (light) absorption loss within a silicon waveguide is typically negligible. However, the energy of two telecom/datacom-band photons does exceed the bandgap energy of silicon. When the energy of two photons within the silicon waveguide exceeds the bandgap energy of silicon, two-photon absorption (TPA) can occur within the silicon waveguide, thus incurring corresponding optical loss within the silicon waveguide. The likelihood of two photons being absorbed in the silicon waveguide increases quadratically with the intensity of light propagating though the silicon waveguide. Therefore, TPA in the silicon waveguide is a second order optical absorption effect that becomes more pronounced at higher optical power.

[0048] While TPA introduces an additional optical loss term, the absorption of the photons in TPA also frees charge carriers (electrons and holes) by promoting them from bound states in the valence band to the conduction band, which produces a carrier plasma that leads to further optical losses that are linear in optical intensity for a fixed plasma density. Because a substantial free-carrier density is produced by TPA, increased free-carrier density generation within the silicon waveguide can be an even more significant contributor to linear optical loss within the silicon waveguide at higher optical powers. The free-carriers (electrons and holes) generated within the silicon waveguide produce high free-carrier absorption (FCA) optical losses. The FCA optical loss is linear with the optical intensity for a given carrier density, with the free-carriers in turn being created by a second-order process, thus being a third-order effect. The optical absorption loss (dI/dz) in the silicon waveguide due to TPA and free-carrier optical absorption is represented in Equation 1, where (I) is the light intensity, (z) is the light propagation distance along the silicon waveguide, (α') is the linear optical loss coefficient due to free-carriers within the silicon waveguide, (τ) is the free-carrier lifetime within the silicon waveguide, and (β') is the TPA absorption coefficient.

$$(dI/dz) = -\alpha' \cdot \tau \cdot \beta' I^3. \qquad \text{Equation 1}$$

[0049] With regard to Equation 1, in order to reduce the third-order optical losses, the coefficient ($\alpha' \cdot \tau \cdot \beta'$) in front of the cubic term of intensity (I3) needs to be minimized. One way to do this is to reduce the free-carrier lifetime (τ). The free-carrier lifetime (τ) is determined by free-carrier diffusion and the free-carrier recombination rate. There is also a modified free-carrier recombination rate near waveguide boundaries, depending on the surface quality (roughness) and chemistry, which affects the free-carrier lifetime (τ), and is described by a surface recombination velocity coefficient. The free-carrier lifetime (τ) within the silicon waveguide is a key parameter, which can be reduced in various ways. For example, in some embodiments, the silicon waveguide fabrication is adjusted to increase the free-carrier recombination rate in silicon and/or at waveguide interfaces so as to correspondingly reduce the free-carrier lifetime (τ) within the silicon waveguide. In some embodiments, free-carriers are removed from the silicon waveguide by applying an electric field in the region of the silicon waveguide in which the free-carriers are generated. More specifically, an electric field is formed across a core region of the silicon waveguide. This electric field pulls the charged free-carriers (electrons and holes) away from the core region of the silicon waveguide through which the primary optical mode propagates, so that the probability of charged free-carriers causing optical absorption loss within the core region is substantially reduced. This process is known as carrier sweep out and can significantly reduce optical losses that scale with free-carrier concentration, such as the third-order optical absorption losses discussed above with regard to Equation 1. In some embodiments, in order to generate the electric field across the core region of the silicon waveguide for free-carrier sweep out, diodes (such as PN diode configurations) are formed across/along the silicon waveguide and are operated in reverse bias mode.

[0050] It should be understood and appreciated that non-linear optical losses due to TPA and free-carrier absorption are relevant in many types and/or configurations of optical waveguides, including, but not limited to, bus waveguides, drop waveguides, ring resonators, ring modulators, and microring resonators/modulators (such as annular-shaped, disk-shaped, racetrack-shaped, and other similar circuitously shaped resonators/modulators), which are collectively referred to as traveling-wave resonators (TWRs). Also, it should be understood and appreciated that non-linear optical losses are relevant in many types and/or configurations of photonic crystals and other standing wave resonators (SWRs).

[0051] As discussed above, at high optical power, TPA within the silicon waveguide becomes more likely, which increases the probability of free-carrier generation within the silicon waveguide. The resulting free-carrier absorption within the silicon waveguide leads to high optical losses within the silicon waveguide. In many applications that require optical coupling from a bus waveguide to a ring resonator or other (e.g., output) waveguide, the optical power in the bus waveguide may be high enough that TPA is a serious problem. In optical data communication systems, a bus waveguide may carry many wavelengths of light, corresponding to different communication channels. The combination of these multiple wavelengths of light corresponds to a high optical power density within the bus waveguide. Therefore, it is of interest to improve optical data communication systems to mitigate the adverse optical losses caused by TPA and free-carrier absorption within silicon waveguides of various photonic components.

[0052] FIG. **1**A shows a top view of an example ring modulator **100** that implements a rib ring **107**, in accordance with some embodiments. The ring modulator **100** is positioned so that the rib ring **107** is located within an evanescent optical coupling distance from an optical waveguide **113**, e.g., a bus optical waveguide. The rib ring **107** and the optical waveguide **113** are formed as respective full-height (full-thickness) silicon regions. The rib ring **107** and the optical waveguide **113** are surrounded by partial-height (partial-thickness) silicon regions **117**, **119**, and **121**. The partial-height silicon region **117** extends around an inside wall of the rib ring **107**. The partial-height silicon region **119** extends around an outside wall of the rib ring **107**. The partial-height silicon region **119** also extends between the rib ring **107** and the optical waveguide **113**. The partial-height silicon region **119** also extends along a first wall of the optical waveguide **113** that faces toward the ring modulator **100**. The partial-height silicon region **121** extends along a second wall of the optical waveguide **113** that is on an opposite side of the optical waveguide **113** from the first wall of the optical waveguide **113**.

[0053] A full-height (full-thickness) silicon region **105** extends along an outer radial periphery of the portion of the partial-height silicon region **119** that extends radially around the rib ring **107**. A full-height (full-thickness) silicon region **116** extends along the partial-height silicon region **119** on a side of the partial-height silicon region **119** that is located away from the optical waveguide **113**. A full-height (full-thickness) silicon region **115** extends along the partial-height silicon region **121** on a side of the partial-height silicon region **121** that is located away from the optical waveguide **113**. Full-height (full-thickness) silicon regions **109** and **111** are formed along an inner side of the partial-height silicon region **117** that is located away from the rib ring **107**.

[0054] The ring modulator **100** is formed within an optical cladding material **103** that includes an inner optical cladding material **1031**, a first outer optical cladding material **10301**, and a second outer optical cladding material **10302**. More specifically, in some embodiments, the inner optical cladding material **1031** is circumscribed by a combination of the full-height (full-thickness) silicon regions **109** and **111** and the partial-height silicon region **117**. Also, the ring modulator **100** is circumscribed by the first outer optical cladding material **10301**. Also, the second outer optical cladding material **10302** is present along a side of the full-height (full-thickness) silicon region **115** that is located away from the ring modulator **100**.

[0055] A number of inner electrical contacts **123** (shown as black dots) are formed in electrical connection with the full-height (full-thickness) silicon region **109** along the inner side of the partial-height silicon region **117** that is located away from the rib ring **107**. Also, a number outer electrical contacts **125** (shown as black dots) are formed in electrical connection with the full-height (full-thickness) silicon region **105** that extends along the outer radial periphery of the portion of the partial-height silicon region **119** that extends radially around the rib ring **107**.

[0056] The ring modulator **100** has an N-type doping region **127** that includes a portion of the rib ring **107**, a portion of the partial-height silicon region **117**, the full-height (full-thickness) silicon region **109**, and two narrow end strips of the partial-height silicon region **119**. The ring modulator **100** also has a P-type doping region **129** that includes a portion of the rib ring **107**, a portion of the partial-height silicon region **119** that extends radially around the rib ring **107**, and the full-height (full-thickness) silicon region **105**. The N-type doping region **127** and the P-type doping region **129** interface with each other within the rib ring **107** to form a PN junction diode within the rib ring **107**.

[0057] FIG. **1**B shows a vertical cross-section through the rib ring **107** and the optical waveguide **113** at a location of their closest approach to each other, referenced as View A-A in FIG. **1**A, in accordance with some embodiments. The rib ring **107** and the optical waveguide **113** have a thickness **135**, which corresponds to a full-thickness of silicon. Each of the partial-height (partial-thickness) silicon regions **117**, **119**, and **121** have a thickness **133**, which is less than the thickness **135**. The optical waveguide **113** has a width **137**. The rib ring **107** has a radial width **139**. The optical waveguide **113** approaches the rib ring **107** such that a minimum (non-zero) separation distance **141** exists between the optical waveguide **113** and the rib ring **107**. An optical coupling region **120** (indicated by dashed line in FIG. **1**A) exists in which the optical waveguide **113** is located within an evanescent optical coupling distance of the rib ring **107**. Because the optical waveguide **113** semi-tangentially approaches the rib ring **107** (without contacting the rib ring **107**), the optical coupling region **120** exists along an optical coupling length **122** of the optical waveguide **113** and along an optical coupling length **124** of the rib ring **107**, as shown in FIG. **1**A.

[0058] FIG. **1**C shows a vertical cross-section through the rib ring **107** and the full-height (full-thickness) silicon regions **109** and **105**, referenced as View B-B in FIG. **1**A, in accordance with some embodiments. Each of the rib ring **107**, the inner silicon region **109**, and the outer silicon region **105** has the thickness **135**, which corresponds to the full-thickness of silicon. The rib ring **107** is separated from the inner silicon region **109** by a radial distance **143** over which the partial-height (partial-thickness) silicon region **117** is formed to have the thickness **133**. The rib ring **107** is separated from the outer silicon region **105** by a radial distance **145** over which the partial-height (partial-thickness) silicon region **119** is formed to have the thickness **133**. The rib ring **107** has the radial width **139**, which is substantially consistent around the circumference of the rib ring **107**. The vertical cross-section of FIG. **1**C also extends through one of the inner electrical contacts **123** positioned in electrical connection with the inner silicon region **109**. The vertical cross-section of FIG. **1**C also extends through one of the outer electrical contacts **125** positioned in electrical connection with the outer silicon region **105**. FIG. **1**C shows an interface **130** (dashed line) between the N-type doping region **127** and the P-type doping region **129** within the rib ring **107** to form the PN junction diode along the interface **130**. In some embodiments, the N-type doping region **127** overlaps the P-type doping region **129** within the rib ring **107** over an area **131**. Alternatively, in some embodiments, the P-type doping region **129** overlaps the N-type doping region **127** within the rib ring **107** over the area **131**. It should be understood that the area **131** of overlap between the N-type doping region **127** and the P-type doping region **129** extends azimuthally about a center **140** of the ring modulator **100** and around a portion of the rib ring **107** where the P-type doping region **129** is formed, as shown in FIG. **1**A.

[0059] FIGS. **1**D through **1**G show a succession of fabrication processes performed to arrive at the example ring modulator **100** of FIGS. **1**A through IC, in accordance with some embodiments. FIG. **1**D shows a top view of a configuration of full-height (full-thickness) silicon **101** formed within the cladding material **103**, in accordance with some embodiments. The configuration of full-height (full-thickness) silicon **101** has the thickness **135** as shown in FIGS. **1**B and 1C. A portion of the configuration of full-height (full-thickness) silicon **101** is used to form the ring modulator **100**. Another portion of the configuration of full-height (full-thickness) silicon **101** is used to form part of the optical waveguide **113** that extends past the ring modulator **100**.

[0060] FIG. **1**E shows a top view of the configuration of full-height (full-thickness) silicon **101** with portions of the full-height (full-thickness) silicon **101** etched away to form the partial-height (partial-thickness) silicon regions **117**, **119**, and **121**, in accordance with some embodiments. The partial-height (partial-thickness) silicon regions **117**, **119**, and **121** have the thickness **133**, as shown in FIGS. **1**B and **1**C, which is less than the thickness **135**. The partial-height (partial-thickness) silicon regions **117**, **119**, and **121** are configured and positioned such that a first remaining portion of the full-height (full-thickness) silicon **101** forms the rib ring **107**, and such that a second remaining portion of the full-height (full-thickness) silicon **101** forms the outer silicon region **105**, and such that a third remaining portion of the full-height (full-thickness) silicon **101** forms the inner silicon regions **109** and **111**, and such that a fourth remaining portion of the full-height (full-thickness) silicon **101** forms the optical waveguide **113**, and such that a fifth remaining portion of the full-height (full-thickness) silicon **101** forms the full-height (full-thickness) silicon region **116**, and such that a sixth remaining portion of the full-height (full-thickness) silicon **101** forms the full-height (full-thickness) silicon region **115**.

[0061] FIG. **1**F shows a top view of the partially formed ring modulator **100** of FIG. **1**E with formation of the inner electrical contacts **123** and the outer electrical contacts **125**, in accordance with some embodiments. The inner electrical contacts **123** are formed in electrical connection with the inner full-height (full-thickness) silicon region **109**. The outer electrical contacts **125** are formed in electrical connection with the outer full-height (full-thickness) silicon region **105**. In some embodiments, the inner electrical contacts **123** are substantially uniformly azimuthally spaced along the inner full-height (full-thickness) silicon region **109**. In some embodiments, the outer electrical contacts **125** are substantially uniformly azimuthally spaced along the outer full-height (full-thickness) silicon region **105**.

[0062] FIG. **1**G shows a top view of the partially formed ring modulator **100** of FIG. **1**F with the N-type doping region **127** formed, in accordance with some embodiments. The N-type doping region **127** is formed within the silicon of the inner full-height (full-thickness) silicon region **109**, and within the partial-height (partial-thickness) silicon region **117** that extends along the inner full-height (full-thickness) silicon region **109**, and within a portion of the rib ring **107** that extends along a same azimuthal angular span **142** as the inner full-height (full-thickness) silicon region **109** about the center **140** of the ring modulator **100**. The azimuthal angular span **142** is defined such that the N-type doping region **127** is not formed over the inner full-height (full-thickness) silicon regions **111**. The N-type doping region **127** electrically interfaces with the inner electrical contacts **123**.

[0063] FIG. **1**A shows the top view of the ring modulator **100** of FIG. **1**G with the P-type doping region **129** formed, in accordance with some embodiments. The P-type doping region **129** is formed within the silicon of the outer full-height (full-thickness) silicon region **105**, and within the partial-height (partial-thickness) silicon region **119** that extends along the outer full-height (full-thickness) silicon region **105**, and within a portion of the rib ring **107** that extends along a same azimuthal angular span **151** as the outer full-height (full-thickness) silicon region **105** about the center **140** of the ring modulator **100**. The P-type doping region **129** electrically interfaces with the outer electrical contacts **125**.

[0064] The rib ring **107** is formed as a rib optical waveguide that loops back into itself. A portion of the rib ring **107** extends through the optical coupling region **120** in which there is no doping region formed. Each of the P-type doping region **129** and the N-type doping region **127** is doped with impurity ions to form a lateral PN junction diode. More specifically, the P-type doping region **129** forms the laterally outer portion of the lateral PN junction diode that is doped with acceptor impurity atoms. Conversely, the N-type doping region **127** forms the laterally inner portion of the lateral PN junction diode that is doped with donor impurity atoms. In this manner, the N-type doping region **127** and the P-type doping region **129** are doped with opposite polarity. The interface between the N-type doping region **127** and the P-type doping region **129** within the rib ring **107** is the PN junction of the lateral PN junction diode. At the PN junction within the rib ring **107**, the free electrons diffuse into the P-type doping region **129** and the holes (electron vacancies) diffuse into the N-type doping region **127**, which causes a depletion region to form along the PN junction within the rib ring **107**. The portion of the N-type doping region **127** formed within the partial-height (partial-thickness) silicon region **117** provides an electrically conductive path between the inner electrical contacts **123** and the depletion region formed along the PN junction within the rib ring **107**. Also, the portion of the P-type doping region **129** formed within the partial-height (partial-thickness) silicon region **119** provides an electrically conductive path between the outer electrical contacts **125** and the depletion region formed along the PN junction within the rib ring **107**.

[0065] The outer electrical contacts **125** are electrically connected to the P-type doping region **129**. The inner electrical contacts **123** are electrically connected to the N-type doping region **127**. Therefore, with the lateral PN junction diode electrically connected in a reverse-biased manner to an electrical voltage source, the inner electrical contacts **123** of the N-type doping region **127** are electrically connected to the anode of the electrical voltage source, and the outer electrical contacts **125** of the P-type doping region **129** are electrically connected to the cathode of the electrical voltage source. The outer electrical contacts **125** are positioned far enough from the rib ring **107** to reduce optical absorption of the light traveling through the rib ring **107** by metal and silicided regions that form the outer electrical contacts **125**. Also, the inner electrical contacts **123** are positioned far enough from the rib ring **107** to reduce optical absorption of the light traveling through the rib ring **107** by metal and silicided regions that form the inner electrical contacts **123**.

[0066] The lateral PN junction diode configuration of the ring modulator **100**, with the inner electrical contacts **123** positioned on the inner radii and the outer electrical contacts **125** positioned on the outer radii, provides several advantages, such as low junction series electrical resistance to the PN junction diode and low parasitic electrical capacitance between doped regions located away/apart from the rib ring **107** through which light travels within the ring modulator **100**. Also, in the ring modulator **100**, the lateral PN junction diode configuration does not extend into the optical coupling region **120** between the rib ring **107** and the optical waveguide **113** because positioning of outer electrical contacts **125** and implantation of dopants within the optical coupling region **120** would cause adverse optical absorption loss for light traveling through the optical waveguide **113**.

[0067] In wavelength division multiplexed (WDM) configurations, the optical waveguide **113** carries/guides light of multiple wavelength channels. In the WDM configurations, optical absorption loss in the optical waveguide **113** affects all wavelength channels. Also, in systems that have multiple instances of the ring modulators optically coupled to the same optical waveguide **113**, e.g., to the same bus optical waveguide, the optical absorption loss in the optical waveguide **113** accumulates from all ring modulators that are optically coupled to the optical waveguide **113**. As mentioned above, the ring modulator **100** avoids causing adverse optical absorption loss in the optical waveguide **113** by not having the lateral PN junction diode within the optical coupling region **120**. However, by not having the lateral PN junction diode formed within the optical coupling region **120**, the optical modulator efficiency of the ring modulator **100** is reduced.

[0068] In some embodiments, the N-type doping region **127** and the P-type doping region **129** are extended through the optical coupling region **120** and electrical contacts are placed on the side of the optical waveguide **113** that is opposite from the side of the optical waveguide **113** along which the ring modulator is positioned. In these embodiments, the dopants and electrical contacts within the optical coupling region **120** can adversely contribute to optical absorption loss within the optical waveguide **113** and adversely increase electrical series resistance in the lateral PN junction diode. Therefore, it is of interest to have a ring modulator in which the lateral PN junction diode is extended into the optical coupling region of the ring modulator without adversely affecting optical absorption loss in the optical waveguide to which the ring modulator is optically coupled and without adversely increasing the electrical series resistance in the lateral PN junction diode of the ring modulator.

[0069] FIG. **2**A shows the top view of the partially formed ring modulator **100** of FIG. **1**F with annotations for computation of the optical coupling length **124** of the rib ring **107** along which the lateral PN junction diode is excluded, in accordance with some embodiments. It is considered that the outer electrical contacts **125** are placed a minimum distance (d) from each of the rib ring **107** and the optical waveguide **113** in order to reduce optical absorption loss caused by the electrical contacts **125**. It is also considered that the rib ring **107** has an outer radius (R). It is also considered that a minimum ring-to-waveguide coupling gap distance (g) exists between the rib ring **107** and the optical waveguide **113**. It is also considered that the portion of the optical waveguide **113** that extends past the ring modulator **100** has a substantially straight configuration. Given the above-mentioned considerations, an angular region (θ) that cannot accommodate a lateral PN junction diode within the ring modulator **100** is given by Equation 2.

$$\theta = 2\cos^{-1}\left(\frac{R+g-d}{R+d}\right). \qquad \text{Equation 2}$$

[0070] In an example embodiment, for R=5 micrometers, d=1.5 micrometers, and g=0.25 micrometer, the angular region (θ) is 120°, which means that one-third of the ring modulator **100** cannot accommodate the lateral PN junction diode. In this example embodiment, the efficiency of the ring modulator **100** (measured as wavelength shift per volt) is reduced by one-third as compared to a having a lateral PN junction diode formed around a total circumferential length of the rib ring **107**.

[0071] FIG. **2**B shows a top view of a partially formed ring modulator **100**A that has a second optical waveguide **113**A and a second optical coupling region **120**A, in accordance with some embodiments. The ring modulator **100**A is a variation of the ring modulator **100** of FIG. **1**A. The partial-height silicon region **119** extends between the rib ring **107** and the second optical waveguide **113**A. A partial-height silicon region **121**A extends along a side of the second optical waveguide **113**A that is opposite from the rib ring **107**. A full-height (full-thickness) silicon region **115**A extends along the partial-height silicon region **121**A on a side of the partial-height silicon region **121**A that is located away from the second optical waveguide **113**A. The second optical waveguide **113**A is positioned on an opposite side of the ring modulator **100**A relative to the optical waveguide **113**. In some embodiments, the second optical waveguide **113**A is configured in the same manner as the optical waveguide **113**, and is positioned to extend parallel with the optical waveguide **113** past the ring modulator **100**A. In these embodiments that have both the optical waveguide **113** and the second optical waveguide **113**A, the angular region (θ) that cannot accommodate a lateral PN junction diode within the ring modulator **100**A, as given by Equation 2, occurs at a first location for the optical waveguide **113** and at a second location for the optical waveguide **113**A. Therefore, in the example embodiment in which R=5 micrometers, d=1.5 micrometers, and g=0.25 micrometer, the total angular region (θ) of the ring modulator **100**A that cannot accommodate the lateral PN junction diode is 240°, which is two-thirds of the total circumferential length of the rib ring **107**. In this example embodiment, the efficiency of the ring modulator **100**A (measured as wavelength shift per volt) is reduced by two-thirds as compared to a having a lateral PN junction diode formed around a total circumferential length of the rib ring **107**.

[0072] FIG. **3**A shows a top view of a ring modulator **300** that implements an interdigitated diode configuration within an optical coupling region **320** between an optical waveguide **313** and a rib ring **307** of the ring modulator **300** in order to optimize modulation efficiency while minimizing optical loss in the optical waveguide **313**, in accordance with some embodiments. In some embodiments, the ring modulator **300** and optical waveguide **313** configuration of FIG. **3**A is implemented within a photonic integrated circuit (PIC). The rib ring **307** is a ring-shaped optical waveguide. The ring modulator **300** is positioned so that the rib ring **307** is located within an evanescent optical coupling distance from the optical waveguide **313**. The rib ring **307** is formed as a rib optical waveguide that loops back into itself. A portion of the rib ring **307** extends through the optical coupling region **320**. The rib ring **307** and the optical waveguide **313** are formed as respective full-height (full-thickness) silicon regions. The rib ring **307** and the optical waveguide **313** are surrounded by partial-height (partial-thickness) silicon regions **317**, **319**, and **321**. The partial-height silicon region **317** extends around an inside wall of the rib ring **307**. The partial-height silicon region **319** extends around an outside wall of the rib ring **307**. The partial-height silicon region **319** also extends between the rib ring **307** and the optical waveguide **313**. The partial-height silicon region **319** also extends along a first wall of the optical waveguide **313** that faces toward the ring modulator **300**. The partial-height silicon region **321** extends along a second wall of the optical waveguide **313** that is on an opposite side of the optical waveguide **313** from the first wall of the optical waveguide **313**.

[0073] A full-height (full-thickness) silicon region **305** extends along an outer radial periphery of the portion of the partial-height silicon region **319** that extends along an azimuthal angular span **326** about a center **340** of the ring modulator **300** radially outside of the rib ring **307**. The center **340** of the ring modulator **300** is also the center **340** of the ring shape of the rib ring **307**. A full-height (full-thickness) silicon region **316** extends along the partial-height silicon region **119** on a side of the partial-height silicon region **119** that is located away from the optical waveguide **313**. A full-height (full-thickness) silicon region **315** extends along the partial-height silicon region **321** on a side of the partial-height silicon region **321** that is located away from the optical waveguide **313**. Full-height (full-thickness) silicon regions **309** and **311** are formed along an inner side of the partial-height silicon region **317** that is located away from the rib ring **307**.

[0074] The ring modulator **300** is formed within an optical cladding material **303** that includes an inner optical cladding material **3031**, a first outer optical cladding material **30301**, and a second outer optical cladding material **30302**. More specifically, in some embodiments, the inner optical cladding material **3031** is circumscribed by a combination of the full-height (full-thickness) silicon regions **309** and **311** and the partial-height silicon region **317**. Also, the ring modulator **300** is circumscribed by the first outer optical cladding material **30301**. Also, the second outer optical cladding material **30302** is present along a side of the full-height (full-thickness) silicon region **315** that is located away from the ring modulator **300**.

[0075] A number of inner electrical contacts **323** (shown as black dots) are formed in electrical connection with the full-height (full-thickness) silicon region **309** along the inner side of the partial-height silicon region **317** that is located away from the rib ring **307**. Also, a number of inner electrical contacts **324** (shown as black dots) are formed in electrical connection with the full-height (full-thickness) silicon regions **311** along the inner side of the partial-height silicon region **317** that is located away from the rib ring **307**. Also, a number outer electrical contacts **325** (shown as black dots) are formed in electrical connection with the full-height (full-thickness) silicon region **305** that extends along the outer radial periphery of the portion of the partial-height silicon region **319** that extends radially around the rib ring **307**.

[0076] The ring modulator **300** has an N-type doping region **327** that is formed within a portion of the rib ring **307**, a portion of the partial-height silicon region **317**, and the full-height (full-thickness) silicon region **309**. The N-type doping region **327** includes a number of tab-shaped N-type doping regions **327**T that each project inward from the rib ring **307** toward the center **340** of the ring modulator **300** to form respective portions of the interdigitated diode configuration within the optical coupling region **320**. The ring modulator **300** also has a P-type doping region **329** that is formed within a portion of the rib ring **307**, a portion of the partial-height silicon region **319** that extends radially around the rib ring **307**, and the full-height (full-thickness) silicon region **305**.

[0077] The P-type doping region **329** also includes a number of tab-shaped P-type doping regions **329**T that each project inward from the rib ring **307** toward the center **340** of the ring modulator **300** to form respective portions of the interdigitated diode configuration within the optical coupling region **320**. The tab-shaped N-type doping regions **327**T and the tab-shaped P-type doping regions **329**T alternate in placement with respect to each other along the curvature of the rib ring **307** within the optical coupling region **320**. In this manner, the tab-shaped N-type doping regions **327**T and the tab-shaped P-type doping regions **329**T collectively form the interdigitated diode configuration within the optical coupling region **320**. In some embodiments, adjacently positioned ones of the tab-shaped N-type doping regions **327**T and the tab-shaped P-type doping regions **329**T are separated from each other by a non-doped portion of the partial-height silicon region **317**.

[0078] The N-type doping region **327** and the P-type doping region **329** interface with each other within the rib ring **307** to form a PN junction diode within the optical coupling region **320**. The tab-shaped N-type doping regions **327**T and the tab-shaped P-type doping regions **329**T provide respective electrically conductive pathways from the PN junction diode within the rib ring **307** to respective ones of the inner electrical contacts **324**. In this manner, the N-type doping region **327** of the PN junction diode within the rib ring **307**, within the optical coupling region **320**, is electrically connected to a first node of an electrical circuit through each of the tab-shaped N-type doping regions **327**T and corresponding inner electrical contacts **324**. Also, the

P-type doping region **329** of the PN junction diode within the rib ring **307**, within the optical coupling region **320**, is electrically connected to a second node of an electrical circuit through each of the tab-shaped P-type doping regions **329**T and corresponding inner electrical contacts **324**. Therefore, it should be understood that in the ring modulator **300**, the PN junction diode formed within the rib ring **307** extends through the optical coupling region **320** as indicated by arrow **322**.

[0079] FIG. **3**B shows a vertical cross-section through the rib ring **307** and the optical waveguide **313** at a location of their closest approach to each other, referenced as View A-A in FIG. **3**A, in accordance with some embodiments. The rib ring **307** and the optical waveguide **313** have a thickness **335**, which corresponds to a full-thickness of silicon. Each of the partial-height (partial-thickness) silicon regions **317**, **319**, and **321** have a thickness **333**, which is less than the thickness **335**. The optical waveguide **313** has a width **337**. The rib ring **307** has a radial width **339**. The optical waveguide **313** approaches the rib ring **307** such that a minimum (non-zero) separation distance **341** exists between the optical waveguide **313** and the rib ring **307**. The optical coupling region **320** (indicated by the dashed line in FIG. **3**A) exists in which the optical waveguide **313** is located within an evanescent optical coupling distance of the rib ring **307**. Because the optical waveguide **313** semi-tangentially approaches the rib ring **307** (without contacting the rib ring **307**), the optical coupling region **320** exists along an optical coupling length **328** of the optical waveguide **313** and along the optical coupling length **322** of the rib ring **307**, as shown in FIG. **3**A.

[0080] FIG. **3**C shows a vertical cross-section through the rib ring **307** and the full-height (full-thickness) silicon regions **309** and **305**, referenced as View B-B in FIG. **3**A, in accordance with some embodiments. Each of the rib ring **307**, the inner silicon region **309**, and the outer silicon region **305** has the thickness **335**, which corresponds to the full-thickness of silicon. The rib ring **307** is separated from the inner silicon region **309** by a radial distance **343** over which the partial-height (partial-thickness) silicon region **317** is formed to have the thickness **333**. The rib ring **307** is separated from the outer silicon region **305** by a radial distance **345** over which the partial-height (partial-thickness) silicon region **319** is formed to have the thickness **333**. The rib ring **307** has the radial width **339**, which is substantially consistent around the entire circumference of the rib ring **307**. The vertical cross-section of FIG. **3**C also extends through one of the inner electrical contacts **323** positioned in electrical connection with the inner silicon region **309**. The vertical cross-section of FIG. **3**C also extends through one of the outer electrical contacts **325** positioned in electrical connection with the outer silicon region **305**. FIG. **3**C shows an interface **330** (dashed line) between the N-type doping region **327** and the P-type doping region **329** within the rib ring **307** to form the PN junction diode along the interface **330**. In some embodiments, the N-type doping region **327** overlaps the P-type doping region **329** within the rib ring **307** over an area **331**. Alternatively, in some embodiments, the P-type doping region **329** overlaps the N-type doping region **327** within the rib ring **307** over the area **331**. It should be understood that the area **331** of overlap between the N-type doping region **327** and the P-type doping region **329** extends around the circumference of the rib ring **307**, including through the optical coupling region **320**.

[0081] FIGS. **3**D through **3**J show a succession of fabrication processes performed to arrive at the example ring modulator **300** of FIGS. **3**A through **3**C, in accordance with some embodiments. FIG. **3**D shows a top view of a configuration of full-height (full-thickness) silicon **301** formed within the cladding material **303**, in accordance with some embodiments. The configuration of full-height (full-thickness) silicon **301** has the thickness **335** as shown in FIGS. **3**B and **3**C. A portion of the configuration of full-height (full-thickness) silicon **301** is used to form the ring modulator **300**. Another portion of the configuration of full-height (full-thickness) silicon **301** is used to form the optical waveguide **313** that extends past the ring modulator **300**.

[0082] FIG. **3**E shows a top view of the configuration of full-height (full-thickness) silicon **301** of FIG. **3**D with portions of the full-height (full-thickness) silicon **301** etched away to form the partial-height (partial-thickness) silicon regions **317**, **319**, and **321**, in accordance with some embodiments. The partial-height (partial-thickness) silicon regions **317**, **319**, and **321** have the thickness **333**, as shown in FIGS. **3**B and **3**C, which is less than the full-thickness **335**. The partial-height (partial-thickness) silicon regions **317**, **319**, and **321** are configured and positioned such that a first remaining portion of the full-height (full-thickness) silicon **301** forms the rib ring **307**, and such that a second remaining portion of the full-height (full-thickness) silicon **301** forms the outer silicon region **305**, and such that a third remaining portion of the full-height (full-thickness) silicon **301** forms the inner silicon regions **309** and **311**, and such that a fourth remaining portion of the full-height (full-thickness) silicon **301** forms the optical waveguide **313**, and such that a fifth remaining portion of the full-height (full-thickness) silicon **301** forms the full-height (full-thickness) silicon region **316**, and such that a sixth remaining portion of the full-height (full-thickness) silicon **301** forms the full-height (full-thickness) silicon region **315**.

[0083] FIG. **3**F shows a top view of the partially formed ring modulator **300** of FIG. **3**E with formation of the inner electrical contacts **323**, the inner electrical contacts **324**, and the outer electrical contacts **325**, in accordance with some embodiments. The inner electrical contacts **323** are formed in electrical connection with the inner full-height (full-thickness) silicon region **309**. The inner electrical contacts **324** are formed in electrical connection with the inner full-height (full-thickness) silicon regions **311**, respectively. The outer electrical contacts **325** are formed in electrical connection with the outer full-height (full-thickness) silicon region **305**. In some embodiments, the inner electrical contacts **323** are substantially uniformly azimuthally spaced about the center **340** of ring modulator **300** along the inner full-height (full-thickness) silicon region **309**. In some embodiments, the outer electrical contacts **325** are substantially uniformly azimuthally spaced about the center **340** of the ring modulator **300** along the outer full-height (full-thickness) silicon region **305**.

[0084] FIG. **3**G shows a top view of the partially formed ring modulator **300** of FIG. **3**F with formation of the N-type doping region **327** and the tab-shaped N-type doping regions **327**T, in accordance with some embodiments. The N-type doping region **327** is formed within the silicon of the inner full-height (full-thickness) silicon region **309**, and within the partial-height (partial-thickness) silicon region **317** that extends along the inner full-height (full-thickness) silicon region **309**, and within a portion of the rib ring **307** around the circumference of the rib ring **307**. The tab-shaped N-type doping regions **327**T are integrally formed with the N-type doping region **327**, such that each of the tab-shaped N-type doping regions **327**T is an inward extending portion of the N-type doping region **327**.

[0085] FIG. **3**H shows an isolated top view of the N-type doping region **327** and the tab-shaped N-type doping regions **327**T, in accordance with some embodiments. Each of the tab-shaped N-type doping regions **327**T extends inward toward the center **340** of the ring modulator **300** so as to extend over a corresponding one of the inner full-height (full-thickness) silicon regions **311**, and so as to electrically interface with a corresponding one of the inner electrical contacts **324**. Also, the N-type doping region **127** that extends over the inner full-height (full-thickness) silicon region **309** electrically interfaces with the inner electrical contacts **323**.

[0086] FIG. **3**A shows the top view of the ring modulator **300** of FIG. **3**G with formation of the P-type doping region **329** and the tab-shaped P-type doping regions **329**T, in accordance with some embodiments. The P-type doping region **329** is formed within the silicon of the outer full-height (full-thickness) silicon region **305**, and within the partial-height (partial-thickness) silicon region **319** that extends along the outer full-height (full-thickness) silicon region **305**, and within a portion of the rib ring **307** around an entire circumferential span of the rib ring **307**. The tab-shaped P-type doping regions **329**T are integrally formed with the P-type doping region **329**, such that each of the tab-shaped P-type doping regions **329**T is an inward extending portion of the P-type doping region **329**.

[0087] FIG. **3**I shows an isolated top view of the P-type doping region **329** and the tab-shaped P-type doping regions **329**T, in accordance with some embodiments. Each of the tab-shaped P-type doping regions **329**T extends inward toward the center **340** of the ring modulator **300** so as to extend over a corresponding one of the inner full-height (full-thickness) silicon regions **311**, and so as to electrically interface with a corresponding one of the inner electrical contacts **324**. Also, the P-type doping region **129** that extends over the outer full-height (full-thickness) silicon region **305** electrically interfaces with the outer electrical contacts **325**.

[0088] FIG. **3**J shows an isolated top view of the P-type doping region **329** and the tab-shaped P-type doping regions **329**T positioned in relation with the N-type doping region **327** and the tab-shaped N-type doping regions **327**T, in accordance with some embodiments. In some embodiments, such as shown in FIGS. **3**J and **3**A, adjacently formed ones of the tab-shaped P-type doping regions **329**T and the tab-shaped N-type doping regions **327**T are azimuthally spaced apart from each other about the center **340** of the ring modulator **300**, such that they are not in direct physical contact with each other.

[0089] Each of the P-type doping region **329**, the tab-shaped P-type doping regions **329**T, the N-type doping region **327**, and the tab-shaped N-type doping regions **327**T is doped with impurity ions to form the lateral PN junction diode. In some embodiments, the P-type doping region **329** and tab-shaped P-type doping regions **329**T are doped with acceptor impurity atoms, and the N-type doping region **327** and the tab-shaped N-type doping regions **327**T are doped with donor impurity atoms. In these embodiments, the N-type doping region **327** and the P-type doping region **329** are doped with opposite polarity. The interface between the N-type doping region **327** and the P-type doping region **329** within the rib ring **307** is the PN junction of the lateral PN junction diode. At the PN junction within the rib ring **307**, the free electrons diffuse into the P-type doping region **329** and the holes (electron vacancies) diffuse into the N-type doping region **327**, which causes a depletion region to form along the PN junction within the rib ring **307**.

[0090] It should be appreciated that in the ring modulator **300**, the PN junction diode formed by the P-type doping region **329** and the N-type doping region **327** extends through the optical coupling region **320**. Within the optical coupling region **320**, the tab-shaped N-type doping regions **327**T formed within the partial-height (partial-thickness) silicon region **317** provide respective electrically conductive paths between the inner electrical contacts **324** and the depletion region formed along the PN junction within the rib ring **307**. Also, within the optical coupling region **320**, the tab-shaped P-type doping regions **329**T formed within the partial-height (partial-thickness) silicon region **317** provide respective electrically conductive paths between the inner electrical contacts **324** and the depletion region formed along the PN junction within the rib ring **307**. Along the rib ring **307** outside of the optical coupling region **320**, the N-type doping region **327** formed within the partial-height (partial-thickness) silicon region **317** provides an electrically conductive path between the inner electrical contacts **323** and the depletion region formed along the PN junction within the rib ring **307**. Also, along the rib ring **307** outside of the optical coupling region **320**, the P-type doping region **329** formed within the partial-height (partial-thickness) silicon region **319** provides an electrically conductive path between the outer electrical contacts **325** and the depletion region formed along the PN junction within the rib ring **307**.

[0091] In some embodiments, with the lateral PN junction diode within the rib ring **307** electrically connected in a reverse-biased manner to an electrical voltage source, the inner electrical contacts **323** of the N-type doping region **327** and the inner electrical contacts **324** of the tab-shaped N-type doping regions **327**T are electrically connected to the anode of the electrical voltage source. Also, in these embodiments, with the lateral PN junction diode within the rib ring **307** electrically connected in a reverse-biased manner to the electrical voltage source, the outer electrical contacts **325** of the P-type doping region **329** and the inner electrical contacts **324** of the tab-shaped P-type doping regions **329**T are electrically connected to the cathode of the electrical voltage source. The outer electrical contacts **325** are positioned far enough from the rib ring **307** to reduce optical absorption of the light traveling through the rib ring **307** by metal and silicided regions that form the outer electrical contacts **325**. Also, the inner electrical contacts **324** are positioned far enough from the rib ring **307** to reduce optical absorption of the light traveling through the rib ring **307** by metal and silicided regions that form the inner electrical contacts **324**.

[0092] In the ring modulator **300**, the lateral PN junction diode extends into the optical coupling region **320** of the ring modulator **300** without adversely affecting optical absorption loss in the optical waveguide **313** to which the ring modulator **300** is optically coupled. Also, positioning of the tab-shaped N-type doping regions **327**T and the tab-shaped P-type doping regions **329**T on the inside of the rib ring **307** so as to extend toward the center **340** of ring modulator **300** enables the lateral PN junction diode to extend through the optical coupling region **320** of the ring modulator **300** without adversely affecting optical absorption loss in the optical waveguide **313** to which the ring modulator **300** is optically coupled. Additionally, by having the multiple tab-shaped N-type doping regions **327**T and tab-shaped P-type doping regions **329**T alternatively positioned along the arc of the rib ring **307** within the optical coupling region **320**, the electrical series resistance in the lateral PN junction diode of the ring modulator **300** is not adversely increased by having the lateral PN junction diode extend through the optical coupling region **320**.

[0093] The ring modulator **300** uses the interdigitated PN junction diode design (interdigitation of the tab-shaped N-type doping regions **327**T and the tab-shaped P-type doping regions **329**T) in the portion of the rib ring **307** that passes through the optical coupling region **320**, while using a different non-interdigitated PN junction diode design in the portion of the rib ring **307** that does not pass through the optical coupling region **320**. Within the optical coupling region **320**, the inner electrical contacts **324** are positioned along the inner region of the ring modulator **300**, far from the rib ring **307** and even farther from the optical waveguide **313**, so as to avoid optical absorption loss in the coupling optical waveguides **307** and **313**. The interdigitated tab-shaped N-type doping regions **327**T and tab-shaped P-type doping regions **329**T alternate polarity (alternate cathode and anode) within the optical coupling region **320**.

[0094] It should be understood that there is more flexibility in the design of the portions of the ring modulator **300** that are away from the optical coupling region **320**. For example, in the region of the ring modulator **300** away from the optical coupling region **320**, the inner electrical contacts **323** and the N-type doping region **327** are placed on the inner side of the rib ring **307**, and the outer electrical contacts **325** and the P-type doping region **329** are placed on the outer side of the rib ring **307**, so as to reduce and/or minimize the series electrical resistance of the ring modulator **300**. All of the inner electrical contacts **323** that are electrically connected to the N-type doping region **327** and all of the inner electrical contacts **324** that are connected to a corresponding one of the tab-shaped N-type doping regions **327**T are collectively electrically connected to a same first electrical node. Similarly, all of the outer electrical contacts **325** that are electrically connected to the P-type doping region **329** and all of the inner electrical contacts **324** that are connected to a corresponding one of the tab-shaped P-type doping regions **329**T are collectively electrically connected to a same second electrical node that is different and electrically separated from the first electrical node. In various embodiments, electrically conductive structures, e.g., metal traces/wires, and electrically conductive via structures are formed in and/or through different levels of the semiconductor device in which the ring modulator **300** is formed in order to electrically connect all of the inner electrical contacts **323** that are electrically connected to the N-type doping region **327** and all of the inner electrical contacts **324** that are connected to a corresponding one of the tab-shaped N-type doping regions **327**T to the same first electrical node. Also, in various embodiments, electrically conductive structures, e.g., metal traces/wires, and electrically conductive via structures are formed in and/or through different levels of the semiconductor device in which the ring modulator **300** is formed in order to electrically connect all of the outer electrical contacts **325** that are electrically connected to the P-type doping region **329** and all of the inner electrical contacts **324** that are connected to a corresponding one of the tab-shaped P-type doping regions **329**T to the same second electrical node.

[0095] In accordance with the foregoing, the ring resonator **300** includes a built-in interdigitated PN junction diode for modulating an optical signal propagating through the optical waveguide **313**. The optical mode supported by the ring resonator **300** has significant power density that overlaps the depletion region of the PN junction diode within the rib ring **307**. By changing the voltage differential between the anode and cathode of the PN junction diode within the rib ring **307**, charge carriers can be added to or removed from the depletion region of the PN junction within the rib ring **307** in a controlled manner, which provides for changing of the refractive index and optical absorption coefficient of the rib ring **307** in a controlled manner by way of the plasma effect, which in turn provides for changing of the amplitude and phase of the light that is transmitted on through the optical waveguide **313** past the ring modulator **300** in a controlled manner. In some embodiments, the PN junction diode within the rib ring **307** of the ring modulator **300** is operated in a reversed bias manner to enable fast charge transport and correspondingly high optical modulation data rates.

[0096] In some embodiments, the optical waveguide **313** carries multiple wavelength channels of light, with only one of the multiple wavelength channels of light being coupled into and modulated by the ring resonator **300**. In some embodiments, such as in WDM systems, multiple instances of the ring resonator **300** are optically coupled to the same optical waveguide **313**, with each of the ring resonators **300** tuned to modulate a different one of the multiple wavelength channels of light propagating through the optical waveguide **313**. The metal of the inner electrical contacts **324** absorbs light across all wavelengths. Therefore, by having the inner electrical contacts **324** positioned away from the optical waveguide **313**, e.g., by a distance greater than or equal to about one micrometer, within each instance of the ring modulator **300**, it is possible to avoid introduction and accumulation of excess optical absorption loss of the light propagating through the optical waveguide **313** across every wavelength channel of light.

[0097] FIGS. **3**A through **3**J show a portion of a photonic integrated circuit. The photonic integrated circuit includes a first optical waveguide **307** that has a ring shape. The first optical waveguide **307** is formed of silicon and has a first vertical height **335**. The photonic integrated circuit also includes an inner silicon region **317** formed circumferentially along an inner side of the first optical waveguide **307**. The inner silicon region **317** has a second vertical height **333** that is less than the first vertical height **335**. The photonic integrated circuit also includes a second optical waveguide **313** configured to semi-tangentially approach an outer side of the first optical waveguide **307** and extend past the first optical waveguide **307**, such that an optical coupling region **320** exists between a portion of the second optical waveguide **313** and a portion of the first optical waveguide **307**. The photonic integrated circuit also includes an N-type doping region **327** formed within the first optical waveguide **307** and the inner silicon region **317**. The N-type doping region **327** includes multiple tab-shaped N-type doping regions **327**T formed within the optical coupling region **320**. Each of the multiple tab-shaped N-type doping regions **327**T is formed to project inward toward a center **340** of the ring shape of the first optical waveguide **307**. The photonic integrated circuit also includes a P-type doping region **329** formed within the first optical waveguide **307** and the inner silicon region **317**. The P-type doping region **329** includes multiple tab-shaped P-type doping regions **329**T formed within the optical coupling region **320**. Each of the multiple tab-shaped P-type doping regions **329**T is formed to project inward toward the center **340** of the ring shape of the first optical waveguide **307**. Positions of the multiple tab-shaped N-type doping regions **327**T alternate with positions of the multiple tab-shaped P-type doping regions **329**T along the portion of the first optical waveguide **307** within the optical coupling region **320**, such that the multiple tab-shaped N-type doping regions **327**T and the multiple tab-shaped P-type doping regions **329**T collectively form an interdigitated PN diode configuration within the first optical waveguide **307** within the optical coupling region **320**.

[0098] The N-type doping region **327** includes a connecting portion **327**C that is contiguously formed within the first optical waveguide **307** through the optical coupling region **320** and that is contiguously formed with each of the multiple tab-shaped N-type doping regions **327**T. The P-type doping region **329** includes a connecting portion **329**C that is contiguously formed within the first optical waveguide **307** through the optical coupling region **320** and that is contiguously formed with each of the multiple tab-shaped P-type doping regions **329**T. Adjacently positioned ones of the multiple tab-shaped N-type doping regions **327**T and the multiple tab-shaped P-type doping regions **329**T are physically separated from each other, such as shown in FIG. **3**J. The connecting portion **327**C of the N-type doping region **327** is in physical contact with the connecting portion **329**C of the P-type doping region **329** within the first optical waveguide **307**, such as shown in FIG. **3**B. The connecting portion **329**C of the P-type doping region **329** extends below the connecting portion **327**C of the N-type doping region **327**, such as shown in FIG. **3**B. The connecting portion **327**C of the N-type doping region **327** is circumscribed by an annular segment **329**CA of the connecting portion **329**C of the P-type doping region **329**.

[0099] The photonic integrated circuit also includes multiple inner electrical contacts **324** respectively physically connected to each of the multiple tab-shaped N-type doping regions **327**T and each of the multiple tab-shaped P-type doping regions **329**T. Each of the multiple inner electrical contacts **324** is positioned at an inner edge of the inner silicon region **317** relative to the center **340** of the ring shape of the first optical waveguide **307**. In some embodiments, the multiple tab-shaped N-type doping regions **327**T are electrically connected to a first electrical node by way of corresponding ones of the multiple inner electrical contacts **324**. Also, the multiple tab-shaped P-type doping regions **329**T are electrically connected to a second electrical node by way of corresponding ones of the multiple inner electrical contacts **324**. The second electrical node is electrically separated from the first electrical node. In some embodiments, the first electrical node is electrically connected to an anode of an electrical voltage source, and the second electrical node is electrically connected to a cathode of the electrical voltage source, such that the interdigitated PN diode configuration is reverse-biased.

[0100] The photonic integrated circuit also includes an outer silicon region **319** is formed circumferentially along the outer side of the first optical waveguide **307**. The outer silicon region **319** is formed between the first optical waveguide **307** and the second optical waveguide **313**. The outer silicon region **319** has a third vertical height **333** that is less than the first vertical height **335** of the first optical waveguide **307**. In some embodiments, the outer silicon region **319** is not doped. In some embodiments, the third vertical height **333** of the outer silicon region **319** is substantially equal to the second vertical height **333** of the inner silicon region **317**. In some embodiments, a vertical height **335** of the second optical waveguide **313** is substantially equal to the first vertical height **335** of the first optical waveguide **307**.

[0101] The first optical waveguide **307**, the second optical waveguide **313**, the outer silicon region **319**, and the inner silicon region **317** are respective parts of a contiguous silicon structure. The contiguous silicon structure has a planar bottom surface that forms a respective bottom surface of each of the first optical waveguide **307**, the second optical waveguide **313**, the outer silicon region **319**, and the inner silicon region **317**. In some embodiments, the outer silicon region **319** and the inner silicon region **317** are etched regions of the contiguous silicon structure.

[0102] The N-type doping region **327** includes an azimuthal portion that is contiguously formed within the inner silicon region **317** along an azimuthal angular span **326** about the center **340** of the ring shape of the first optical waveguide **307** outside of the interdigitated PN diode configuration within the optical coupling region **320**. The P-type doping region **329** includes an azimuthal portion that is contiguously formed within the outer silicon region **319** along the azimuthal angular span **326**. The N-type doping region **327** and the P-type doping region **329** interface with each other to form a continuous PN diode configuration within the first optical waveguide **307** along the azimuthal angular span **326**.

[0103] In some embodiments, the photonic integrated circuit includes a first set of multiple electrical contacts **324** respectively physically connected to each of the multiple tab-shaped N-type doping regions **327**T and each of the multiple tab-shaped P-type doping regions **329**T. Each electrical contact **324** of the first set of multiple electrical contacts **324** is positioned at an inner edge of the inner silicon region **317** relative to the center **340** of the ring shape of the first optical waveguide **307**. The multiple tab-shaped N-type doping regions **327**T are electrically connected to a first electrical node by way of corresponding ones of the first set of multiple electrical contacts **324**. The multiple tab-shaped P-type doping regions **329**T are electrically connected to a second electrical node by way of corresponding ones of the first set of multiple electrical contacts **324**. The first electrical node is electrically connected to an anode of an electrical voltage source, and the second electrical node is electrically connected to a cathode of the electrical voltage source, such that the interdigitated PN diode configuration is reverse-biased. A second set of multiple electrical contacts **323** are positioned in a spaced apart configuration along an inner edge of the inner silicon region **317** along the azimuthal angular span **326** about the center **340** of the ring shape of the first optical waveguide **307** outside of the interdigitated PN diode configuration. In some embodiments, the second set of multiple electrical contacts **323** are electrically connected to optical modulation circuitry. A third set of multiple electrical contacts **325** are positioned in a spaced apart configuration along an outer edge of the outer silicon region **319** along the azimuthal angular span **326** about the center **340** of the ring shape of the first optical waveguide **307** outside of the interdigitated PN diode configuration. In some embodiments, the third set of multiple electrical contacts **325** are electrically connected to the optical modulation circuitry.

[0104] FIG. **4**A shows a top view of a ring modulator **400** that implements a first interdigitated diode configuration within a first optical coupling region **420** and that implements a second interdigitated diode configuration within a second optical coupling region **470**, in accordance with some embodiments. The first interdigitated diode configuration within the first optical coupling region **420** is formed by multiple tab-shaped N-type doping regions **427**T and multiple tab-shaped P-type doping regions **429**T, where the tab-shaped N-type doping regions **427**T and the tab-shaped P-type doping regions **429**T are alternately positioned with respect to each other. The first optical coupling region **420** is between a rib ring **407** of the ring modulator **400** and an optical waveguide **413**. The rib ring **407** is a ring-shaped optical waveguide. The second optical coupling region **470** is between the rib ring **407** of the ring modulator **400** and an optical waveguide **463**. The rib ring **407** is formed as a rib optical waveguide that loops back into itself. A portion of the rib ring **407** extends through the optical coupling region **420**. Another portion of the rib ring **407** extends through the optical coupling region **470**. The ring modulator **400** is configured to optimize modulation efficiency while minimizing optical loss in each of the optical waveguide **413** and the optical waveguide **463**. The ring modulator **400** is positioned so that the rib ring **407** is located within an evanescent optical coupling distance from the optical waveguide **413**. The ring modulator **400** is also positioned so that the rib ring **407** is located within an evanescent optical coupling distance from the optical waveguide **463**. In some embodiments, the ring modulator **400**, the optical waveguide **413**, and the optical waveguide **463** configuration of FIG. **4**A is implemented within a PIC.

[0105] The rib ring **407** and each of the optical waveguide **413** and the optical waveguide **463** are formed as respective full-height (full-thickness) silicon regions. The rib ring **407** is surrounded by a partial-height (partial-thickness) silicon region **419**. More specifically, the partial-height silicon region **419** extends around an outside wall of the rib ring **407**. The rib ring **407** itself surrounds a partial-height (partial-thickness) silicon region **417**. More specifically, the partial-height silicon region **417** extends around an inside wall of the rib ring **407**. The optical waveguide **413** is bracketed by the partial-height (partial-thickness) silicon region **419** on a side of the optical waveguide **413** that faces toward the ring modulator **400**, and is bracketed by a partial-height (partial-thickness) silicon region **421** on a side of the optical waveguide **413** that faces away from the ring modulator **400**. The partial-height silicon region **419** also extends between the rib ring **407** and the optical waveguide **413**. The optical waveguide **463** is bracketed by the partial-height (partial-thickness) silicon region **419** on a side of the optical waveguide **463** that faces toward the ring modulator **400**, and is bracketed by a partial-height (partial-thickness) silicon region **471** on a side of the optical waveguide **463** that faces away from the ring modulator **400**. The partial-height silicon region **419** also extends between the rib ring **407** and the optical waveguide **463**.

[0106] A full-height (full-thickness) silicon region **405** extends along an outer radial periphery of a portion of the partial-height silicon region **419** that extends along an azimuthal angular span **428** about a center **440** of the ring modulator **400** radially outside of the rib ring **407**. The center **440** of the ring modulator **400** is also the center **440** of the ring shape of the rib ring **407**. A full-height (full-thickness) silicon region **406** extends along an outer radial periphery of a portion of the partial-height silicon region **419** that extends along an azimuthal angular span **430** about the center **440** of the ring modulator **400** radially outside of the rib ring **407**. A full-height (full-thickness) silicon region **416** extends along the partial-height silicon region **419** on a side of the partial-height silicon region **419** that is located away from the optical waveguide **413**. A full-height (full-thickness) silicon region **415** extends along the partial-height silicon region **421** on a side of the partial-height silicon region **421** that is located away from the optical waveguide **413**. A full-height (full-thickness) silicon region **418** extends along the partial-height silicon region **419** on a side of the partial-height silicon region **419** that is located away from the optical waveguide **463**. A full-height (full-thickness) silicon region **475** extends along the partial-height silicon region **471** on a side of the partial-height silicon region **471** that is located away from the optical waveguide **463**. Full-height (full-thickness) silicon regions **409**, **410**, **411**, and **412** are formed along an inner side of the partial-height silicon region **417** that is located away from the rib ring **407**.

[0107] The ring modulator **400** is formed within an optical cladding material **403** that includes an inner optical cladding material **4031**, a first outer optical cladding material **40301**, second outer optical cladding material **40302**, and a third outer optical cladding material **40303**. More specifically, in some embodiments, the inner optical cladding material **4031** is circumscribed by a combination of the full-height (full-thickness) silicon regions **409**, **410**, **411**, and **412** and the partial-height silicon region **417**. The first outer optical cladding material **40301** is present along a side of the full-height (full-thickness) silicon region **475** that is located away from the ring modulator **400**. The second outer optical cladding material **40302** is present outside of the ring modulator **400** and between the full-height (full-thickness) silicon regions **416** and **418**. The third outer optical cladding material **40303** is present along a side of the full-height (full-thickness) silicon region **415** that is located away from the ring modulator **400**.

[0108] A number of inner electrical contacts **423** (shown as black dots) are formed in electrical connection with the full-height (full-thickness) silicon region **409** along the inner side of the partial-height silicon region **417** that is located away from the rib ring **407**. A number of inner electrical contacts **423** (shown as black dots) are formed in electrical connection with the full-height (full-thickness) silicon region **410** along the inner side of the partial-height silicon region **417** that is located away from the rib ring **407**. Also, a number of inner electrical contacts **424** (shown as black dots) are formed in electrical connection with the full-height (full-thickness) silicon regions **411**, respectively, along the inner side of the partial-height silicon region **417** that is located away from the rib ring **407**. Also, a number of inner electrical contacts **426** (shown as black dots) are formed in electrical connection with the full-height (full-thickness) silicon regions **412**, respectively, along the inner side of the partial-height silicon region **417** that is located away from the rib ring **407**. Also, a number outer electrical contacts **425** (shown as black dots) are formed in electrical connection with the full-height (full-thickness) silicon region **405** that extends along the outer radial periphery of the portion of the partial-height silicon region **419** that extends radially around the rib ring **407**. Also, a number outer electrical contacts **425** (shown as black dots) are formed in electrical connection with the full-height (full-thickness) silicon region **406** that extends along the outer radial periphery of the portion of the partial-height silicon region **419** that extends radially around the rib ring **407**.

[0109] The ring modulator **400** has an N-type doping region **427**R that includes portions of the rib ring **407**, portions of the partial-height silicon region **417**, and the full-height (full-thickness) silicon region **409**. The ring modulator **400** also has an N-type doping region **427**L that includes portions of the rib ring **407**, portions of the partial-height silicon region **417**, and the full-height (full-thickness) silicon region **410**. The ring modulator **400** also has a number of tab-shaped N-type doping regions **427**T that each project inward from the rib ring **407** toward the center **440** of the ring modulator **400** to form respective portions of the interdigitated diode configuration within the optical coupling region **420**. Each of the tab-shaped N-type doping regions **427**T within the optical coupling region **420** includes a corresponding portion of the rib ring **407**, a corresponding portion of the partial-height silicon region **417**, and a corresponding one of the full-height (full-thickness) silicon regions **411**. Similarly, the ring modulator **400** has a number of tab-shaped N-type doping regions **427**T that each project inward from the rib ring **407** toward the center **440** of the ring modulator **400** to form respective portions of the interdigitated diode configuration within the optical coupling region **470**. Each of the tab-shaped N-type doping regions **427**T within the optical coupling region **470** includes a corresponding portion of the rib ring **407**, a corresponding portion of the partial-height silicon region **417**, and a corresponding one of the full-height (full-thickness) silicon regions **412**.

[0110] The ring modulator **400** has a P-type doping region **429**R that includes portions of the rib ring **407**, portions of the partial-height silicon region **419**, and the full-height (full-thickness) silicon region **405**. The ring modulator **400** also has a P-type doping region **429**L that includes portions of the rib ring **407**, portions of the partial-height silicon region **419**, and the full-height (full-thickness) silicon region **406**. The ring modulator **400** also has a number of tab-shaped P-type doping regions **429**T that each project inward from the rib ring **407** toward the center **440** of the ring modulator **400** to form respective portions of the interdigitated diode configuration within the optical coupling region **420**. Each of the tab-shaped P-type doping regions **429**T within the optical coupling region **420** includes a corresponding portion of the rib ring **407**, a corresponding portion of the partial-height silicon region **417**, and a corresponding one of the full-height (full-thickness) silicon regions **411**. Similarly, the ring modulator **400** has a number of tab-shaped P-type doping regions **429**T that each project inward from the rib ring **407** toward the center **440** of the ring modulator **400** to form respective portions of the interdigitated diode configuration within the optical coupling region **470**. Each of the tab-shaped N-type doping regions **429**T within the optical coupling region **470** includes a corresponding portion of the rib ring **407**, a corresponding portion of the partial-height silicon region **417**, and a corresponding one of the full-height (full-thickness) silicon regions **412**.

[0111] The tab-shaped N-type doping regions **427**T and the tab-shaped P-type doping regions **429**T alternate in placement with respect to each other along the curvature of the rib ring **407** within the optical coupling region **420**. In this manner, the tab-shaped N-type doping regions **427**T and the tab-shaped P-type doping regions **429**T collectively form the interdigitated diode configuration within the optical coupling region **420**. Also, the tab-shaped N-type doping regions **427**T and the tab-shaped P-type doping regions **429**T alternate in placement with respect to each other along the curvature of the rib ring **407** within the optical coupling region **470**. In this manner, the tab-shaped N-type doping regions **427**T and the tab-shaped P-type doping regions **429**T collectively form the interdigitated diode configuration within the optical coupling region **470**. In some embodiments, adjacently positioned ones of the tab-shaped N-type doping regions **427**T and the tab-shaped P-type doping regions **429**T are separated from each other by a non-doped portion of the partial-height silicon region **417**.

[0112] The N-type doping regions **427**T and the P-type doping region **429**T interface with each other within the rib ring **407** to form a portion of a PN junction diode within the optical coupling region **420**. Similarly, the N-type doping regions **427**T and the P-type doping region **429**T interface with each other within the rib ring **407** to form a portion of the PN junction diode within the optical coupling region **470**. Also, the N-type doping regions **427**R and the P-type doping region **429**R interface with each other within the rib ring **407** to form a portion of the PN junction diode. Similarly, the N-type doping regions **427**L and the P-type doping region **429**L interface with each other within the rib ring **407** to form a portion of the PN junction diode. The tab-shaped N-type doping regions **427**T and the tab-shaped P-type doping regions **429**T within the optical coupling region **420** provide respective electrically conductive pathways from the PN junction diode within the rib ring **407** to respective ones of the inner electrical contacts **424**. In this manner, the N-type doping regions **427**T of the PN junction diode within the rib ring **407**, within the optical coupling region **420**, are electrically connected to a first node of an electrical circuit through corresponding inner electrical contacts **424**. Also, the P-type doping regions **429**T of the PN junction diode within the rib ring **407**, within the optical coupling region **420**, are electrically connected to a second node of an electrical circuit through corresponding inner electrical contacts **424**. Additionally, the tab-shaped N-type doping regions **427**T and the tab-shaped P-type doping regions **429**T within the optical coupling region **470** provide respective electrically conductive pathways from the PN junction diode within the rib ring **407** to respective ones of the inner electrical contacts **426**. In this manner, the N-type doping regions **427**T of the PN junction diode within the rib ring **407**, within the optical coupling region **470**, are electrically connected to the first node of the electrical circuit through corresponding inner electrical contacts **426**. Also, the P-type doping regions **429**T of the PN junction diode within the rib ring **407**, within the optical coupling region **470**, are electrically connected to the second node of the electrical circuit through corresponding inner electrical contacts **426**.

[0113] In the ring modulator **400**, the PN junction diode formed within the rib ring **407** extends through the optical coupling region **420** as indicated by arrow **422**. Also, the PN junction diode formed within the rib ring **407** extends from the optical coupling region **420** to the optical coupling region **470** as indicated by arrow **428**. Also, the PN junction diode formed within the rib ring **407** extends through the optical coupling region **470** as indicated by arrow **472**. Also, the PN junction diode formed within the rib ring **407** extends from the optical coupling region **470** to the optical coupling region **420** as indicated by arrow **430**. Additionally, in some embodiments, such as shown in FIG. **4**A, the PN junction diode interface within the rib ring **407** between the N-type doping region **427**R and the P-type doping region **429**R is formed in a serpentine configuration **443**, e.g., gear-tooth-shaped configuration, in order to increase the overall interface area of the PN junction diode within the rib ring **407**. Also, in some embodiments, such as shown in FIG. **4**A, the PN junction diode interface within the rib ring **407** between the N-type doping region **427**L and the P-type doping region **429**L is formed in a serpentine configuration **445**, e.g., gear-tooth-shaped configuration, in order to increase the overall interface area of the PN junction diode within the rib ring **407**.

[0114] FIGS. **4**B through **4**J show a succession of fabrication processes performed to arrive at the example ring modulator **400** of FIG. **4**A, in accordance with some embodiments. FIG. **4**B shows a top view of a configuration of full-height (full-thickness) silicon **401** formed within the cladding material **403**, in accordance with some embodiments. A portion of the configuration of full-height (full-thickness) silicon **401** is used to form the ring modulator **400**. Another portion of the configuration of full-height (full-thickness) silicon **401** is used to form the optical waveguides **413** and **463** that extend past the ring modulator **300**.

[0115] FIG. **4**C shows a top view of the configuration of full-height (full-thickness) silicon **401** with portions of the full-height (full-thickness) silicon **401** etched away to form the partial-height (partial-thickness) silicon regions **417**, **419**, **421**, and **471**, in accordance with some embodiments. The thickness of the partial-height (partial-thickness) silicon regions **417**, **419**, **421**, and **471** is less than the thickness of the full-height (full-thickness) silicon **401**. The partial-height (partial-thickness) silicon regions **417**, **419**, **421**, and **471** are configured and positioned such that a first remaining portion of the full-height (full-thickness) silicon **401** forms the rib ring **407**, and such that a second remaining portion of the full-height (full-thickness) silicon **401** forms the outer silicon regions **405** and **406**, and such that a third remaining portion of the full-height (full-thickness) silicon **401** forms the inner silicon regions **409**, **410**, **411**, and **412**, and such that a fourth remaining portion of the full-height (full-thickness) silicon **401** forms the optical waveguide **413**, and such that a fifth remaining portion of the full-height (full-thickness) silicon **401** forms the full-height (full-thickness) silicon region **416**, and such that a sixth remaining portion of the full-height (full-thickness) silicon **401** forms the full-height (full-thickness) silicon region **415**, and such that a seventh remaining portion of the full-height (full-thickness) silicon **401** forms the optical waveguide **463**, and such that a eighth remaining portion of the full-height (full-thickness) silicon **401** forms the full-height (full-thickness) silicon region **418**, and such that a ninth remaining portion of the full-height (full-thickness) silicon **401** forms the full-height (full-thickness) silicon region **475**.

[0116] FIG. **4**D shows a top view of the partially formed ring modulator **400** of FIG. **4**C with formation of the inner electrical contacts **423**, the inner electrical contacts **424**, the inner electrical contacts **426**, and the outer electrical contacts **425**, in accordance with some embodiments. The inner electrical contacts **423** are formed in electrical connection with the inner full-height (full-thickness) silicon regions **409** and **410**. The inner electrical contacts **424** are formed in electrical connection with the inner full-height (full-thickness) silicon regions **411**, respectively. The inner electrical contacts **426** are formed in electrical connection with the inner full-height (full-thickness) silicon regions **412**, respectively. The outer electrical contacts **425** are formed in electrical connection with the outer full-height (full-thickness) silicon regions **405** and **406**. In some embodiments, the inner electrical contacts **423** are substantially uniformly azimuthally spaced about the center **440** of the ring modulator **400** along each of the inner full-height (full-thickness) silicon regions **409** and **410**. In some embodiments, the outer electrical contacts **425** are substantially uniformly azimuthally spaced about the center **440** of the ring modulator **400** along each of the outer full-height (full-thickness) silicon regions **405** and **406**.

[0117] FIG. **4**E shows a top view of the partially formed ring modulator **400** of FIG. **4**D with formation of the N-type doping regions **427**L and **427**R, and the tab-shaped N-type doping regions **427**T, in accordance with some embodiments. The N-type doping region **427**R is formed within the silicon of the inner full-height (full-thickness) silicon region **409**, and within the partial-height (partial-thickness) silicon region **417** that extends along the inner full-height (full-thickness) silicon region **409**, and within an adjoining portion of the rib ring **407**. The N-type doping region **427**R is electrically connected to the inner electrical contacts **423** by way of the inner full-height (full-thickness) silicon region **409**. The N-type doping region **427**L is formed within the silicon of the inner full-height (full-thickness) silicon region **410**, and within the partial-height (partial-thickness) silicon region **417** that extends along the inner full-height (full-thickness) silicon region **410**, and within an adjoining portion of the rib ring **407**. The N-type doping region **427**L is electrically connected to the inner electrical contacts **423** by way of the inner full-height (full-thickness) silicon region **410**. The tab-shaped N-type doping regions **427**T are formed within the optical coupling region **420**, such that each of the tab-shaped N-type doping regions **427**T includes a respective portion of the rib ring **407**, and extends inward across the partial-height (partial-thickness) silicon region **417** toward the center **440** of the ring modulator **400**, and includes a corresponding one of the full-height (full-thickness) silicon regions **411**, so as to electrically connect with a corresponding one of the inner electrical contacts **424**. The tab-shaped N-type doping regions **427**T are also formed within the optical coupling region **470**, such that each of the tab-shaped N-type doping regions **427**T includes a respective portion of the rib ring **407**, and extends inward across the partial-height (partial-thickness) silicon region **417** toward the center **440** of the ring modulator **400**, and includes a corresponding one of the full-height (full-thickness) silicon regions **412**, so as to electrically connect with a corresponding one of the inner electrical contacts **426**. FIG. **4**F shows an isolated top view of the N-type doping regions **427**L and **427**R, and the tab-shaped N-type doping regions **427**T, in accordance with some embodiments.

[0118] FIG. **4**A shows the top view of the ring modulator **400** of FIG. **4**E with formation of the P-type doping regions **429**L and **429**R, and the tab-shaped P-type doping regions **429**T, in accordance with some embodiments. The P-type doping region **429**R is formed within the silicon of the outer full-height (full-thickness) silicon region **405**, and within the partial-height (partial-thickness) silicon region **419** that extends along the outer full-height (full-thickness) silicon region **405**, and within an adjoining portion of the rib ring **407**. The P-type doping region **429**R is electrically connected to the outer electrical contacts **425** by way of the outer full-height (full-thickness) silicon region **405**. The P-type doping region **429**L is formed within the silicon of the outer full-height (full-thickness) silicon region **406**, and within the partial-height (partial-thickness) silicon region **419** that extends along the outer full-height (full-thickness) silicon region **406**, and within an adjoining portion of the rib ring **407**. The P-type doping region **429**L is electrically connected to the outer electrical contacts **425** by way of the outer full-height (full-thickness) silicon region **406**. The tab-shaped P-type doping regions **429**T are formed within the optical coupling region **420**, such that each of the tab-shaped P-type doping regions **429**T includes a respective portion of the rib ring **407**, and extends inward across the partial-height (partial-thickness) silicon region **417** toward the center **440** of the ring modulator **400**, and includes a corresponding one of the full-height (full-thickness) silicon regions **411**, so as to electrically connect with a corresponding one of the inner electrical contacts **424**. The tab-shaped P-type doping regions **429**T are also formed within the optical coupling region **470**, such that each of the tab-shaped P-type doping regions **429**T includes a respective portion of the rib ring **407**, and extends inward across the partial-height (partial-thickness) silicon region **417** toward the center **440** of the ring modulator **400**, and includes a corresponding one of the full-height (full-thickness) silicon regions **412**, so as to electrically connect with a corresponding one of the inner electrical contacts **426**. The tab-shaped P-type doping regions **429**T and the P-type doping regions **429**L and **429**R are integrally formed with each other, so as to be electrically connected to each other. FIG. **4**G shows an isolated top view of the P-type doping regions **429**L and **429**R, and the tab-shaped P-type doping regions **429**T, in accordance with some embodiments.

[0119] FIG. **4**H shows an isolated top view of the P-type doping regions **429**L and **429**R and the tab-shaped P-type doping regions **429**T positioned in relation with the N-type doping regions **427**L and **427**R and the tab-shaped N-type doping regions **427**T, in accordance with some embodiments. In some embodiments, such as shown in FIGS. **4**H and **4**A, adjacently formed ones of the tab-shaped P-type doping regions **429**T and the tab-shaped N-type doping regions **427**T are interfaced with each other within the rib ring **407** to for the PN junction diode interface within the rib ring **407**, but are spaced apart from each other over the partial-height (partial-thickness) silicon region **417** and over the full-height (full-thickness) silicon regions **411** and **412**, so as to form separate electrical conduction pathways.

[0120] FIG. **4**I shows a top view of the ring modulator **400** with the N-type doping regions **427**L and **427**R, and the tab-shaped N-type doping regions **427**T electrically connected to a first electrical node by way of an electrical conductor **481**, in accordance with some embodiments. The electrical conductor **481** is electrically connected to the inner electrical contacts **423**, **424**, and **426** that are electrically connected to one of N-type doping regions **427**R, **427**L, and **427**T.

[0121] FIG. **4**J shows a top view of the ring modulator **400** of FIG. **4**I with the P-type doping regions **429**L and **429**R, and the tab-shaped P-type doping regions **429**T electrically connected to a second electrical node by way of an electrical conductor **483**, in accordance with some embodiments. The electrical conductor **483** is electrically connected to the inner electrical contacts **424** and **426** that are electrically connected to one of N-type doping regions **429**T. Also, the electrical conductor **483** is electrically connected to the outer electrical contacts **425**.

[0122] Each of the P-type doping regions **429**L and **429**R, the tab-shaped P-type doping regions **429**T, the N-type doping regions **427**L and **427**R, and the tab-shaped N-type doping regions **427**T is doped with impurity ions to form the lateral PN junction diode. In some embodiments, the P-type doping regions **429**L and **429**R and tab-shaped P-type doping regions **429**T are doped with acceptor impurity atoms, and the N-type doping regions **427**L and **427**R and the tab-shaped N-type doping regions **427**T are doped with donor impurity atoms. In this manner, the N-type doping regions **427**L, **427**R, **427**T and the P-type doping regions **429**L, **429**R, **429**T are doped with opposite polarity. The interface between the N-type doping regions **427**L, **427**R, **427**T and the P-type doping regions **429**L, **429**R, **429**T within the rib ring **407** is the PN junction of the lateral PN junction diode. At the PN junction within the rib ring **407**, the free electrons diffuse into the P-type doping regions **429**L, **429**R, **429**T, and the holes (electron vacancies) diffuse into the N-type doping regions **427**L, **427**R, **427**T, which causes a depletion region to form along the PN junction within the rib ring **407**. It should be appreciated that in the ring modulator **400**, the PN junction diode formed by the P-type doping regions **429**L, **429**R, **429**T, and the N-type doping region **427**L, **427**R, **427**T extends through both the optical coupling region **420** and the optical coupling region **470**. Within the optical coupling region **420**, the tab-shaped N-type doping regions **427**T formed within the partial-height (partial-thickness) silicon region **417** provide respective electrically conductive paths between the inner electrical contacts **424** and the depletion region formed along the PN junction within the rib ring **407**. Also, within the optical coupling region **420**, the tab-shaped P-type doping regions **427**T formed within the partial-height (partial-thickness) silicon region **417** provide respective electrically conductive paths between the inner electrical contacts **424** and the depletion region formed along the PN junction within the rib ring **407**. Within the optical coupling region **470**, the tab-shaped N-type doping regions **427**T formed within the partial-height (partial-thickness) silicon region **417** provide respective electrically conductive paths between the inner electrical contacts **426** and the depletion region formed along the PN junction within the rib ring **407**. Also, within the optical coupling region **470**, the tab-shaped P-type doping regions **429**T formed within the partial-height (partial-thickness) silicon region **417** provide respective electrically conductive paths between the inner electrical contacts **426** and the depletion region formed along the PN junction within the rib ring **407**. Along the rib ring **407** between the optical coupling region **420** and the optical coupling region **470**, the N-type doping regions **427**L and **427**R formed within the partial-height (partial-thickness) silicon region

417 provide electrically conductive paths between the inner electrical contacts **423** and the depletion region formed along the PN junction within the rib ring **407**. Also, along the rib ring **407** between of the optical coupling region **420** and the optical coupling region **470**, the P-type doping regions **429**L and **429**R formed within the partial-height (partial-thickness) silicon region **419** provide electrically conductive paths between the outer electrical contacts **425** and the depletion region formed along the PN junction within the rib ring **407**.

[0123] In some embodiments, with the lateral PN junction diode within the rib ring **407** electrically connected in a reverse-biased manner to an electrical voltage source, the inner electrical contacts **423** of the N-type doping regions **427**L and **427**R and the inner electrical contacts **424** and **426** of the tab-shaped N-type doping regions **427**T are electrically connected to the anode of the electrical voltage source. Also, in some embodiments, with the lateral PN junction diode within the rib ring **407** electrically connected in a reverse-biased manner to the electrical voltage source, the outer electrical contacts **425** of the P-type doping regions **429**L and **429**R and the inner electrical contacts **424** and **426** of the tab-shaped P-type doping regions **429**T are electrically connected to the cathode of the electrical voltage source. The outer electrical contacts **425** are positioned far enough from the rib ring **407** to reduce optical absorption of the light traveling through the rib ring **407** by metal and silicided regions that form the outer electrical contacts **425**. Also, the inner electrical contacts **424** and **426** are positioned far enough from the rib ring **407** to reduce optical absorption of the light traveling through the rib ring **407** by metal and silicided regions that form the inner electrical contacts **424** and **324**.

[0124] In the ring modulator **400**, the lateral PN junction diode extends into the optical coupling region **420** of the ring modulator **400** without adversely affecting optical absorption loss in the optical waveguide **413** to which the ring modulator **400** is optically coupled. Also, positioning of the tab-shaped N-type doping regions **427**T and the tab-shaped P-type doping regions **429**T on the inside of the rib ring **407** so as to extend toward the center **440** of ring modulator **400** enables the lateral PN junction diode to extend through the optical coupling region **420** of the ring modulator **400** without adversely affecting optical absorption loss in the optical waveguide **413** to which the ring modulator **400** is optically coupled. Additionally, by having the multiple tab-shaped N-type doping regions **427**T and tab-shaped P-type doping regions **429**T alternatively positioned along the arc of the rib ring **407** within the optical coupling region **420**, the electrical series resistance in the lateral PN junction diode of the ring modulator **400** is not adversely increased by having the lateral PN junction diode extend through the optical coupling region **420**.

[0125] In the ring modulator **400**, the lateral PN junction diode extends into the optical coupling region **470** of the ring modulator **400** without adversely affecting optical absorption loss in the optical waveguide **463** to which the ring modulator **400** is optically coupled. Also, positioning of the tab-shaped N-type doping regions **427**T and the tab-shaped P-type doping regions **429**T on the inside of the rib ring **407** so as to extend toward the center **440** of ring modulator **400** enables the lateral PN junction diode to extend through the optical coupling region **470** of the ring modulator **400** without adversely affecting optical absorption loss in the optical waveguide **463** to which the ring modulator **400** is optically coupled. Additionally, by having the multiple tab-shaped N-type doping regions **427**T and tab-shaped P-type doping regions **429**T alternatively positioned along the arc of the rib ring **407** within the optical coupling region **470**, the electrical series resistance in the lateral PN junction diode of the ring modulator **400** is not adversely increased by having the lateral PN junction diode extend through the optical coupling region **470**.

[0126] The ring modulator **400** uses the interdigitated PN junction diode design (interdigitation of the tab-shaped N-type doping regions **427**T and the tab-shaped P-type doping regions **429**T) in the portions of the rib ring **407** that pass through each of the optical coupling regions **420** and **470**, while using a different non-interdigitated PN junction diode design in the portion of the rib ring **407** that does not pass through the optical coupling regions **420** or **470**. Within the optical coupling region **420**, the inner electrical contacts **424** are positioned along the inner region of the ring modulator **400**, far from the rib ring **407** and even farther from the optical waveguide **413**, so as to avoid optical absorption loss in the coupling optical waveguides **407** and **413**. Similarly, within the optical coupling region **470**, the inner electrical contacts **426** are positioned along the inner region of the ring modulator **400**, far from the rib ring **407** and even farther from the optical waveguide **463**, so as to avoid optical absorption loss in the coupling optical waveguides **407** and **463**. The interdigitated tab-shaped N-type doping regions **427**T and tab-shaped P-type doping regions **429**T alternate polarity (alternate cathode and anode) within each of the optical coupling regions **420** and **470**. It should be understood that there is more flexibility in the design of the portions of the ring modulator **400** that are away from the optical coupling regions **420** and **470**. For example, in the regions of the ring modulator **400** away from the optical coupling regions **420** and **470**, the inner electrical contacts **423** and the N-type doping regions **427**L and **427**R are placed on the inner side of the rib ring **407**, and the outer electrical contacts **425** and the P-type doping regions **429**L and **429**R are placed on the outer side of the rib ring **407**, so as to reduce and/or minimize the series electrical resistance of the ring modulator **400**. All of the inner electrical contacts **423** that are electrically connected to the N-type doping regions **427**L and **427**R and all of the inner electrical contacts **424** and **426** that are connected to a corresponding one of the tab-shaped N-type doping regions **427**T are collectively electrically connected to a same first electrical node. Similarly, all of the outer electrical contacts **425** that are electrically connected to the P-type doping regions **429**L and **429**R and all of the inner electrical contacts **424** and **426** that are connected to a corresponding one of the tab-shaped P-type doping regions **429**T are collectively electrically connected to a same second electrical node that is different and electrically separated from the first electrical node. In various embodiments, electrically conductive structures, e.g., metal traces/wires, and electrically conductive via structures are formed in and/or through different levels of the semiconductor device in which the ring modulator **400** is formed in order to electrically connect all of the inner electrical contacts **423** that are electrically connected to the N-type doping regions **427**L and **427**R and all of the inner electrical contacts **424** and **426** that are connected to a corresponding one of the tab-shaped N-type doping regions **427**T to the same first electrical node, such as exemplified by the electrical conductor **481**. In various embodiments, electrically conductive structures, e.g., metal traces/wires, and electrically conductive via structures are formed in and/or through different levels of the semiconductor device in which the ring modulator **400** is formed in order to electrically connect all of the outer electrical contacts **425** that are electrically connected to the P-type doping regions **429**L and **429**R and all of the inner electrical contacts **424** and **426** that are connected to a corresponding one of the tab-shaped P-type doping regions **429**T to the same second electrical node, such as exemplified by the electrical conductor **483**.

[0127] In accordance with the foregoing, the ring resonator **400** includes a built-in diode for modulating an optical signal propagating through the optical waveguide **413** and/or the optical waveguide **463**. The optical mode supported by the ring resonator **400** has significant power density that overlaps the depletion region of the PN junction diode within the rib ring **407**. By changing the voltage differential between the anode and cathode of the PN junction diode within the rib ring **407**, charge carriers can be added to or removed from the depletion region of the PN junction within the rib ring **407** in a controlled manner, which provides for changing of the refractive index and optical absorption coefficient of the rib ring **407** in a controlled manner by way of the plasma effect, which in turn provides for controlled changing of the amplitude and phase of the light that is transmitted on through the optical waveguide **413** and/or the optical waveguide **463** past the ring modulator **400**. In some embodiments, the PN junction diode within the rib ring **407** of the ring modulator **400** is operated in a reversed bias manner to enable fast charge transport and correspondingly high optical modulation data rates.

[0128] In some embodiments, the optical waveguide **413** and/or the optical waveguide **463** carries multiple wavelength channels of light, with only one of the multiple wavelength channels of light being coupled into and modulated by the ring resonator **400**. In some embodiments, such as in WDM systems, multiple instances of the ring resonator **400** are optically coupled to the same optical waveguide **413** and/or the optical waveguide **463**, with each of the ring resonators **400** tuned to modulate a different one of the multiple wavelength channels of light propagating through the optical waveguide **413** and/or the optical waveguide **463**. The metal of the inner electrical contacts **424** and **426** absorbs light across all wavelengths. Therefore, by having the inner electrical contacts **424** and **426** positioned away from the optical waveguides **413** and **463**, respectively, e.g., by a distance greater than or equal to about one micrometer, within each instance of the ring modulator **400**, it is possible to avoid introduction and accumulation of excess absorption loss of the light propagating through the optical waveguides **413** and **463**, respectively, across every wavelength channel of light.

[0129] In some embodiments, the either the optical waveguide **413** or the optical waveguide **463** is utilized as a drop port optical waveguide to tap off a small fraction of the optical power in the ring modulator **400** into a separate photodiode (photodetector) in order to monitor the optical power within the ring modulator **400**. It should be appreciated that the electrical contacts **424** and **426** and associated wiring are positioned so as to avoid introducing adverse optical absorption loss into the optical waveguide **413** or **463** that is being utilized as the drop port optical waveguide, which allows for sufficient optical power to reach the photodiode to enable monitoring of optical power within the ring modulator **400**.

[0130] It should be appreciated that the ring modulator **400** configuration is particularly important for applications in which the wavelength spacing requires ring modulators with relatively high free spectral range (FSR), for which the ring modulator must have a relatively small radius. In such applications the fractional angle of the optical coupling region **420** and/or **470** may be as much as half the angular region of the ring modulator **400**. The interdigitated PN junction diode design of the ring modulator **400** provides for acceptable modulation efficiency even when such large angular spans are required for the optical absorption region **420** and/or **470** due to the ring modulator **400** having a relatively small radius, because the interdigitated PN junction diode extends through the optical absorption region **420** and/or **470**.

[0131] FIGS. **4**A through **4**J show a portion of a photonic integrated circuit. The photonic integrated circuit includes a first optical waveguide **407** that has a ring shape. The first optical waveguide **407** is formed of silicon and has a first vertical height. The photonic integrated circuit also includes an inner silicon region **417** formed circumferentially along an inner side of the first optical waveguide **407**. The inner silicon region **417** has a second vertical height that is less than the first vertical height of the first optical waveguide **407**. The photonic integrated circuit also includes a second optical waveguide **413** configured to semi-tangentially approach an outer side of the first optical waveguide **407** and extend past the first optical waveguide **407** at a first location (of closest approach), such that a first optical coupling region **420** exists between a portion of the second optical waveguide **413** and a first portion of the first optical waveguide **407** about the first location (of closest approach). The photonic integrated circuit also includes a third optical waveguide **463** configured to semi-tangentially approach the outer side of the first optical waveguide **407** and extend past the first optical waveguide **407** at a second location (of closest approach) that is diametrically opposed to the first location (of closest approach of the second optical waveguide **413**) with regard to the ring shape of the first optical waveguide **407**, such that a second optical coupling region **470** exists between a portion of the third optical waveguide **463** and a second portion of the first optical waveguide **407** about the second location (of closest approach).

[0132] The photonic integrated circuit also includes an N-type doping region **427** formed within the first optical waveguide **407** and the inner silicon region **417**. The N-type doping region **427** includes a first set of multiple tab-shaped N-type doping regions **427**T formed within the first optical coupling region **420**. The N-type doping region **427** includes a second set of multiple tab-shaped N-type doping regions **427**T formed within the second optical coupling region **470**. Each of the tab-shaped N-type doping regions **427**T in the first and second sets of multiple tab-shaped N-type doping regions **427**T is formed to project inward toward a center **440** of the ring shape of the first optical waveguide **407**.

[0133] The photonic integrated circuit also includes a P-type doping region **429** formed within the first optical waveguide **407** and the inner silicon region **417**. The P-type doping region **429** including a first set of multiple tab-shaped P-type doping regions **429**T formed within the first optical coupling region **420**. The P-type doping region **429**

includes a second set of multiple tab-shaped P-type doping regions **429**T formed within the second optical coupling region **470**. Each of the tab-shaped P-type doping regions **429**T in the first and second sets of multiple tab-shaped P-type doping regions **429**T is formed to project inward toward the center **440** of the ring shape of the first optical waveguide **407**.

[0134] Positions of the first set of multiple tab-shaped N-type doping regions **427**T alternate with positions of the first set of multiple tab-shaped P-type doping regions **429**T along the first portion of the first optical waveguide **407**, such that the first set of multiple tab-shaped N-type doping regions **427**T and the first set of multiple tab-shaped P-type doping regions **429**T collectively form a first interdigitated PN diode configuration within the first optical waveguide **407** within the first optical coupling region **420**. Positions of the second set of multiple tab-shaped N-type doping regions **427**T alternate with positions of the second set of multiple tab-shaped P-type doping regions **429**T along the second portion of the first optical waveguide **407**, such that the second set of multiple tab-shaped N-type doping regions **427**T and the second set of multiple tab-shaped P-type doping regions **429**T collectively form a second interdigitated PN diode configuration within the first optical waveguide **407** within the second optical coupling region **470**.

[0135] The N-type doping region **427** includes a first connecting portion **427C1** that is formed within the first optical waveguide **407** through the first optical coupling region **420** and that is contiguously formed with each of the first set of multiple tab-shaped N-type doping regions **427**T within the first optical coupling region **420**. The P-type doping region **429** includes a first connecting portion **429C1** that is formed within the first optical waveguide **407** through the first optical coupling region **420** and that is contiguously formed with each of the first set of multiple tab-shaped P-type doping regions **429**T within the first optical coupling region **420**. The N-type doping region **427** includes a second connecting portion **427C2** that is formed within the first optical waveguide **407** through the second optical coupling region **470** and that is contiguously formed with each of the second set of multiple tab-shaped N-type doping regions **427**T within the second optical coupling region **470**. The P-type doping region **429** includes a second connecting portion **429C2** that is formed within the first optical waveguide **407** through the second optical coupling region **470** and that is contiguously formed with each of the second set of multiple tab-shaped P-type doping regions **429**T within the second optical coupling region **470**. Adjacently positioned ones of the first set of multiple tab-shaped N-type doping regions **427**T and the first set of multiple tab-shaped P-type doping regions **429**T are physically separated from each other within the first optical coupling region **420**. Adjacently positioned ones of the second set of multiple tab-shaped N-type doping regions **427**T and the second set of multiple tab-shaped P-type doping regions **429**T are physically separated from each other within the second optical coupling region **470**. The first connecting portion **427C1** of the N-type doping region **427** is in physical contact with the first connecting portion **429C1** of the P-type doping region **429** within the first optical waveguide **407**. The second connecting portion **427C2** of the N-type doping region **427** is in physical contact with the second connecting portion **429C2** of the P-type doping region **429** within the first optical waveguide **407**. In some embodiments, the first connecting portion **429C1** of the P-type doping region **429** extends below the first connecting portion **427C1** of the N-type doping region **427**, and the second connecting portion **429C2** of the P-type doping region **429** extends below the second connecting portion **427C2** of the N-type doping region **427**. In some embodiments, the first connecting portion **427C1** of the N-type doping region **427** is circumscribed by an annular segment of the first connecting portion **429C1** of the P-type doping region **429**. Also, in some embodiments, the second connecting portion **427C2** of the N-type doping region **427** is circumscribed by an annular segment of the second connecting portion **429C2** of the P-type doping region **429**.

[0136] The photonic integrated circuit also includes a first set of multiple inner electrical contacts **424** respectively physically connected to each of the first set of multiple tab-shaped N-type doping regions **427**T and each of the first set of multiple tab-shaped P-type doping regions **429**T within the first optical coupling region **420**. The photonic integrated circuit also includes a second set of multiple inner electrical contacts **426** respectively physically connected to each of the second set of multiple tab-shaped N-type doping regions **427**T and each of the second set of multiple tab-shaped P-type doping regions **429**T within the second optical coupling region **470**. Each of the first set of multiple inner electrical contacts **424** and each of the second set of multiple inner electrical contacts **426** is positioned at an inner edge of the inner silicon region **417** relative to the center **440** of the ring shape of the first optical waveguide **407**. The first set of multiple tab-shaped N-type doping regions **427**T within the first optical coupling region **420** are electrically connected to a first electrical node by way of corresponding ones of the first set of multiple inner electrical contacts **424**. Also, the first set of multiple tab-shaped P-type doping regions **429**T within the first optical coupling region **420** are electrically connected to a second electrical node by way of corresponding ones of the first set of multiple inner electrical contacts **424**. The second electrical node is electrically separated from the first electrical node. The second set of multiple tab-shaped N-type doping regions **427**T within the second optical coupling region **470** are electrically connected to a third electrical node by way of corresponding ones of the second set of multiple inner electrical contacts **426**. Also, the second set of multiple tab-shaped P-type doping regions **429**T within the second optical coupling region **470** are electrically connected to a fourth electrical node by way of corresponding ones of the second set of multiple inner electrical contacts **426**. The fourth electrical node is electrically separated from the third electrical node. In some embodiments, the first electrical node is electrically connected to an anode of a first electrical voltage source, and the second electrical node is electrically connected to a cathode of the first electrical voltage source, such that the first interdigitated PN diode configuration is reverse-biased. Also, in some embodiments, the third electrical node is electrically connected to an anode of a second electrical voltage source, and the fourth electrical node is electrically connected to a cathode of the second electrical voltage source, such that the second interdigitated PN diode configuration is reverse-biased.

[0137] The photonic integrated circuit also includes an outer silicon region **419** formed circumferentially along the outer side of the first optical waveguide **407**. In some embodiments, the outer silicon region **419** is not doped. The outer silicon region **419** is formed between the first optical waveguide **407** and the second optical waveguide **413**. The outer silicon region **419** is also formed between the first optical waveguide **407** and the third optical waveguide **463**. The outer silicon region **419** has a third vertical height that is less than the first vertical height of the first optical waveguide **407**. In some embodiments, the third vertical height of the outer silicon region **419** is substantially equal to the second vertical height of the inner silicon region **417**. In some embodiments, a vertical height of the second optical waveguide **413** is substantially equal to the first vertical height of the first optical waveguide **407**. Also, in some embodiments, a vertical height of the third optical waveguide **463** is substantially equal to the first vertical height of the first optical waveguide **407**.

[0138] In some embodiments, the first optical waveguide **407**, the second optical waveguide **413**, the third optical waveguide **463**, the outer silicon region **419**, and the inner silicon region **417** are respective parts of a contiguous silicon structure. The contiguous silicon structure has a planar bottom surface that forms a respective bottom surface of each of the first optical waveguide **407**, the second optical waveguide **413**, the third optical waveguide **463**, the outer silicon region **419**, and the inner silicon region **417**. In some embodiments, the outer silicon region **419** and the inner silicon region **417** are etched regions of the contiguous silicon structure.

[0139] The N-type doping region **427** includes a first central portion **427**L that is contiguously formed within the inner silicon region **417** along a first azimuthal angular span **430** about the center **440** of the ring shape of the first optical waveguide **407** between the first and second interdigitated PN diode configurations. The P-type doping region **429** includes a first central portion **429**L that is contiguously formed within the outer silicon region **419** along the first azimuthal angular span **430**. The N-type doping region **427** includes a second central portion **427**R that is contiguously formed within the inner silicon region **417** along a second azimuthal angular span **428** about the center **440** of the ring shape of the first optical waveguide **407** between the first and second interdigitated PN diode configurations. The P-type doping region **429** includes a second central portion **429**R that is contiguously formed within the outer silicon region **419** along the second azimuthal angular span **428**. A location of the second azimuthal angular span **428** is diametrically opposed to a location of the first azimuthal angular span **430** with regard to the ring shape of the first optical waveguide **407**. The first central portion **427**L of the N-type doping region **427** and the first central portion **429**L of the P-type doping region **429** interface with each other to form a first continuous PN diode configuration within the first optical waveguide **407** along the first azimuthal angular span **430**. The second central portion **427**R of the N-type doping region **427** and the second central portion **429**R of the P-type doping region **429** interface with each other to form a second continuous PN diode configuration within the first optical waveguide **407** along the second azimuthal angular span **428**. In some embodiments, an interface between the first central portion **427**L of the N-type doping region **427** and the first central portion **429**L of the P-type doping region **429** has a serpentine configuration along the first azimuthal angular span **430**. In some embodiments, an interface between the second central portion **427**R of the N-type doping region **427** and the second central portion **429**R of the P-type doping region **429** has a serpentine configuration along the second azimuthal angular span **428**.

[0140] A first set of multiple electrical contacts **424** are respectively physically connected to each of the first set of multiple tab-shaped N-type doping regions **427**T and each of the first set of multiple tab-shaped P-type doping regions **429**T within the first optical coupling region **420**. Each electrical contact **424** of the first set of multiple electrical contacts **424** is positioned at an inner edge of the inner silicon region **417** relative to the center **440** of the ring shape of the first optical waveguide **407**. The first set of multiple tab-shaped N-type doping regions **427**T are electrically connected to a first electrical node by way of corresponding ones of the first set of multiple electrical contacts **424**. The first set of multiple tab-shaped P-type doping regions **429**T are electrically connected to a second electrical node by way of corresponding ones of the first set of multiple electrical contacts **424**. The first electrical node is electrically connected to an anode of a first electrical voltage source, and the second electrical node is electrically connected to a cathode of the first electrical voltage source, such that the first interdigitated PN diode configuration is reverse-biased.

[0141] A second set of multiple electrical contacts **426** are respectively physically connected to each of the second set of multiple tab-shaped N-type doping regions **427**T and each of the second set of multiple tab-shaped P-type doping regions **429**T within the second optical coupling region **470**. Each electrical contact **426** of the second set of multiple electrical contacts **426** is positioned at an inner edge of the inner silicon region **417** relative to the center **440** of the ring shape of the first optical waveguide **407**. The second set of multiple tab-shaped N-type doping regions **427**T are electrically connected to a third electrical node by way of corresponding ones of the second set of multiple electrical contacts **426**. The second set of multiple tab-shaped P-type doping regions **429**T are electrically connected to a fourth electrical node by way of corresponding ones of the second set of multiple electrical contacts **426**. The third electrical node is electrically connected to an anode of a second electrical voltage source, and the fourth electrical node is electrically connected to a cathode of the second electrical voltage source, such that the second interdigitated PN diode configuration is reverse-biased.

[0142] A third set of multiple electrical contacts **423** are positioned in a spaced apart configuration along an inner edge of the inner silicon region **417** along the first azimuthal angular span **430** between the first and second interdigitated PN diode configurations. A fourth set of multiple electrical contacts **425** are positioned in a spaced apart configuration along an outer edge of the outer silicon region **419** along the first azimuthal angular span **430** between the first and second interdigitated PN diode configurations. A fifth set of multiple electrical contacts **423** are positioned in a spaced apart configuration along an inner edge of the inner silicon region **417** along the second azimuthal angular span **428** between the first and second interdigitated PN diode configurations. A sixth set of multiple electrical contacts **425** are positioned in a spaced apart configuration along an outer edge of the outer silicon region **419** along the second azimuthal angular span **428** between the first and second interdigitated PN diode configurations. In some embodiments, the third, fourth, fifth, and sixth sets of multiple electrical contacts **423**, **425** are electrically connected to optical modulation circuitry.

[0143] FIG. **5**A shows a top view of a ring modulator **500** that implements a circuitous interdigitated diode configuration that extends through both a first optical coupling region **520** and a second optical coupling region **570**, in accordance with some embodiments. The circuitous interdigitated diode configuration is formed in part by a P-type doped region **529** that includes a P-type doped outer rim region **529**R and multiple P-type doped spoke regions **529**S that extend inward from the P-type doped outer rim region **529**R toward a center **540** of the ring modulator **500**. Adjacently positioned ones of the multiple P-type doped spoke regions **529**S are spaced apart from each other in an azimuthal direction about the center **540** of the ring modulator **500**. The circuitous interdigitated diode configuration is also formed in part by multiple tab-shaped N-type doping regions **527**, each of which is positioned within a space between two adjacently positioned ones of the multiple P-type doped spoke regions **529**S. In this manner, the multiple P-type doped spoke regions **529**S and the multiple tab-shaped N-type doping regions **527** are alternately positioned with respect to each other in the azimuthal direction about the center **540** of the ring modulator **500**.

[0144] The first optical coupling region **520** is between a rib ring **507** of the ring modulator **500** and an optical waveguide **513**. The rib ring **507** is a ring-shaped optical waveguide. The center **540** of the ring modulator **500** is also the center **540** of the ring shape of the rib ring **507**. The second optical coupling region **570** is between the rib ring **507** of the ring modulator **500** and an optical waveguide **563**. The rib ring **507** is formed as a rib optical waveguide that loops back into itself. A portion of the rib ring **507** extends through the optical coupling region **520**. Another portion of the rib ring **507** extends through the optical coupling region **570**. The ring modulator **500** is configured to optimize modulation efficiency while minimizing optical loss in each of the optical waveguide **513** and the optical waveguide **563**. The ring modulator **500** is positioned so that the rib ring **507** is located within an evanescent optical coupling distance from the optical waveguide **513**. The ring modulator **500** is also positioned so that the rib ring **507** is located within an evanescent optical coupling distance from the optical waveguide **563**. In some embodiments, the ring modulator **500**, the optical waveguide **513**, and the optical waveguide **563** configuration of FIG. **5**A is implemented within a PIC.

[0145] The rib ring **507** and each of the optical waveguide **513** and the optical waveguide **563** are formed as respective full-height (full-thickness) silicon regions. The rib ring **507** is surrounded by a partial-height (partial-thickness) silicon region **519**. More specifically, the partial-height silicon region **519** extends around an outside wall of the rib ring **507**. The rib ring **507** itself surrounds a partial-height (partial-thickness) silicon region **517**. More specifically, the partial-height silicon region **517** extends around an inside wall of the rib ring **507**. The optical waveguide **513** is bracketed by the partial-height (partial-thickness) silicon region **519** on a side of the optical waveguide **513** that faces toward the ring modulator **500**, and is bracketed by a partial-height (partial-thickness) silicon region **521** on a side of the optical waveguide **513** that faces away from the ring modulator **500**. The partial-height silicon region **519** also extends between the rib ring **507** and the optical waveguide **513**. The optical waveguide **563** is bracketed by the partial-height (partial-thickness) silicon region **519** on a side of the optical waveguide **563** that faces toward the ring modulator **500**, and is bracketed by a partial-height (partial-thickness) silicon region **571** on a side of the optical waveguide **563** that faces away from the ring modulator **500**. The partial-height silicon region **519** also extends between the rib ring **507** and the optical waveguide **563**.

[0146] A full-height (full-thickness) silicon region **505** extends along an outer radial periphery of a portion of the partial-height silicon region **519** that extends along an azimuthal angular span **528** about the center **540** of the ring modulator **500** radially outside of the rib ring **507**. Also, a full-height (full-thickness) silicon region **506** extends along an outer radial periphery of a portion of the partial-height silicon region **519** that extends along an azimuthal angular span **530** about the center **540** of the ring modulator **500** radially outside of the rib ring **507**. A full-height (full-thickness) silicon region **516** extends along the partial-height silicon region **519** on a side of the partial-height silicon region **519** that is located away from the optical waveguide **513**. A full-height (full-thickness) silicon region **515** extends along the partial-height silicon region **521** on a side of the partial-height silicon region **521** that is located away from the optical waveguide **513**. A full-height (full-thickness) silicon region **518** extends along the partial-height silicon region **519** on a side of the partial-height silicon region **519** that is located away from the optical waveguide **563**. A full-height (full-thickness) silicon region **575** extends along the partial-height silicon region **571** on a side of the partial-height silicon region **571** that is located away from the optical waveguide **563**. Full-height (full-thickness) silicon regions **511** are formed along an inner side of the partial-height silicon region **517** that is located away from the rib ring **507**.

[0147] The ring modulator **500** is formed within an optical cladding material **503** that includes an inner optical cladding material **5031**, a first outer optical cladding material **50301**, a second outer optical cladding material **50302**, and a third outer optical cladding material **50303**. More specifically, in some embodiments, the inner optical cladding material **5031** is circumscribed by a combination of the full-height (full-thickness) silicon regions **511** and the partial-height silicon region **517**. The first outer optical cladding material **50301** is present along a side of the full-height (full-thickness) silicon region **575** that is located away from the ring modulator **500**. The second outer optical cladding material **50302** is present outside of the ring modulator **500** and between the full-height (full-thickness) silicon regions **516** and **518**. The third outer optical cladding material **50303** is present along a side of the full-height (full-thickness) silicon region **515** that is located away from the ring modulator **500**.

[0148] A number of inner electrical contacts **523** (shown as black dots) are formed in electrical connection with the full-height (full-thickness) silicon regions **511** over which the multiple tab-shaped N-type doping regions **527** are formed. A number of inner electrical contacts **524** (shown as black dots) are formed in electrical connection with the full-height (full-thickness) silicon regions **511** over which the multiple P-type doped spoke regions **529**S are formed. The P-type doped outer rim region **529**R includes a portion of the rib ring **507**. Each of the multiple P-type doped spoke regions **529**S includes a respective portion of the rib ring **507**, a respective portion of the partial-height silicon region **517**, and a respective one of the full-height (full-thickness) silicon regions **511**. Each of the multiple tab-shaped N-type doping regions **527** includes a respective portion of the rib ring **507**, a respective portion of the partial-height silicon region **517**, and a respective one of the full-height (full-thickness) silicon regions **511**. The tab-shaped N-type doping regions **527** and the P-type doped spoke regions **529**S alternate in placement with respect to each other along the curvature of the rib ring **507** about the center **540** of the ring modulator **500**. In this manner, the tab-shaped N-type doping regions **527**, the P-type doped outer rim region **529**R, and the multiple P-type doped spoke regions **529**S collectively form the circuitous interdigitated diode configuration within the ring modulator **500** that extends through the optical coupling regions **520** and **570**. In some embodiments, adjacently positioned ones of the tab-shaped N-type doping regions **527** and the P-type doped spoke regions **529**S are separated from each other by a non-doped portion of the partial-height silicon region **517**.

[0149] The N-type doping region **527** and the P-type doping region **529** interface with each other within the rib ring **507** to form a PN junction diode within the rib ring **507** that extends through both of the optical coupling regions **520** and **570**. The tab-shaped N-type doping regions **527** provide respective electrically conductive pathways from the PN junction diode within the rib ring **507** to respective ones of the inner electrical contacts **523**. The tab-shaped N-type doping regions **527** are collectively electrically connected through the inner electrical contacts **523** to a first node of an electrical circuit. The P-type doped spoke regions **529**S provide respective electrically conductive pathways from the PN junction diode within the rib ring **507** to respective ones of the inner electrical contacts **524**. The P-type doped outer rim region **529**R and the P-type doped spoke regions **529**S are collectively electrically connected through the inner electrical contacts **524** to a second node of an electrical circuit. In the ring modulator **500**, the PN junction diode formed within the rib ring **507** extends through the optical coupling region **520** as indicated by arrow **522**. Also, the PN junction diode formed within the rib ring **507** extends from the optical coupling region **520** to the optical coupling region **570** as indicated by arrow **528**. Also, the PN junction diode formed within the rib ring **507** extends through the optical coupling region **570** as indicated by arrow **572**. Also, the PN junction diode formed within the rib ring **507** extends from the optical coupling region **570** to the optical coupling region **520** as indicated by arrow **530**.

[0150] FIGS. **5**B through **5**H show various states of fabrication to arrive at the example ring modulator **500** of FIG. **5**A, in accordance with some embodiments. FIG. **5**B shows a top view of a configuration of full-height (full-thickness) silicon **501** formed within the cladding material **503**, in accordance with some embodiments. A portion of the configuration of full-height (full-thickness) silicon **501** is used to form the ring modulator **500**. Another portion of the configuration of full-height (full-thickness) silicon **501** is used to form the optical waveguides **513** and **563** that extend past the ring modulator **500**.

[0151] FIG. **5**C shows a top view of the configuration of full-height (full-thickness) silicon **501** with portions of the full-height (full-thickness) silicon **501** etched away to form the partial-height (partial-thickness) silicon regions **517**, **519**, **521**, and **571**, in accordance with some embodiments. The thickness of the partial-height (partial-thickness) silicon regions **517**, **519**, **521**, and **571** is less than the thickness of the full-height (full-thickness) silicon **501**. The partial-height (partial-thickness) silicon regions **517**, **519**, **521**, and **571** are configured and positioned such that a first remaining portion of the full-height (full-thickness) silicon **501** forms the rib ring **507**, and such that a second remaining portion of the full-height (full-thickness) silicon **501** forms the outer silicon regions **505** and **506**, and such that a third remaining portion of the full-height (full-thickness) silicon **501** forms the inner silicon regions **511**, and such that a fourth remaining portion of the full-height (full-thickness) silicon **501** forms the optical waveguide **513**, and such that a fifth remaining portion of the full-height (full-thickness) silicon **501** forms the full-height (full-thickness) silicon region **516**, and such that a sixth remaining portion of the full-height (full-thickness) silicon **501** forms the full-height (full-thickness) silicon region **515**, and such that a seventh remaining portion of the full-height (full-thickness) silicon **501** forms the optical waveguide **563**, and such that a eighth remaining portion of the full-height (full-thickness) silicon **501** forms the full-height (full-thickness) silicon region **518**, and such that a ninth remaining portion of the full-height (full-thickness) silicon **501** forms the full-height (full-thickness) silicon region **575**. FIG. **5**C also shows formation of the inner electrical contacts **523** and **524** in electrical connection with the full-height (full-thickness) silicon regions **511** positioned along the inner radius of the ring modulator **500**. In some embodiments, the inner electrical contacts **523** and **524** are substantially uniformly azimuthally spaced about the center **540** of the ring modulator **500**.

[0152] FIG. **5**D shows a top view of the partially formed ring modulator **500** of FIG. **5**C having the N-type doping region **527** and the P-type doping region **529** formed thereon, in accordance with some embodiments. The N-type doping regions **527** are electrically connected to respective ones of the inner electrical contacts **523** by way of respective ones of the inner full-height (full-thickness) silicon regions **511**. The P-type doped spoke regions **529**S are electrically connected to respective ones of the inner electrical contacts **524** by way of respective ones of the inner full-height (full-thickness) silicon regions **511**.

[0153] FIG. **5**E shows an isolated top view of the N-type doping regions **527**, in accordance with some embodiments. FIG. **5**F shows an isolated top view of the P-type doping region **529**, including the P-type doped outer rim region **529**R and multiple P-type doped spoke regions **529**S, in accordance with some embodiments. The P-type doped outer rim region **529**R and the multiple P-type doped spoke regions **529**S are integrally formed with each other, so as to be electrically connected to each other. FIG. **5**G shows an isolated view of the N-type doping regions **527** and the P-type doping region **529** positioned relative to each other as in the ring modulator **500**, in accordance with some embodiments.

[0154] FIG. **5**H shows the top view of the ring modulator **500** of FIG. **5**D with the N-type doping regions **527** electrically connected to a first electrical node by way of an electrical conductor **581**, in accordance with some embodiments. The electrical conductor **581** is electrically connected to the inner electrical contacts **523** that are electrically connected to one of N-type doping regions **527**. FIG. **5**H also shows the P-type doping region **529** electrically connected to a second electrical node by way of an electrical conductor **583** by way of the P-type doped spoke regions **529**S and corresponding inner electrical contacts **524**.

[0155] Each of the P-type doping region **529** and the N-type doping regions **527** is doped with impurity ions to form the lateral PN junction diode within the rib ring **507**. In some embodiments, the P-type doping region **529** is doped with acceptor impurity atoms, and the N-type doping regions **527** are doped with donor impurity atoms. In this manner, the N-type doping regions **527** and the P-type doping region **529** are doped with opposite polarity. The interface between the N-type doping regions **527** and the P-type doping region **529** within the rib ring **507** is the PN junction of the lateral PN junction diode. At the PN junction within the rib ring **507**, the free electrons diffuse into the P-type doping region **529**, and the holes (electron vacancies) diffuse into the N-type doping regions **527**, which causes a depletion region to form along the PN junction within the rib ring **507**. It should be appreciated that in the ring modulator **500**, the PN junction diode formed by the P-type doping region **529** and the N-type doping regions **527** extends through both the optical coupling region **520** and the optical coupling region **570**. Within each of the optical coupling regions **520** and **570**, the N-type doping regions **527** formed within the partial-height (partial-thickness) silicon region **517** provide respective electrically conductive paths between the inner electrical contacts **523** and the depletion region formed along the PN junction within the rib ring **507**. Also, within each of the optical coupling regions **520** and **570**, the P-type doped spoke regions **529**S formed within the partial-height (partial-thickness) silicon region **517** provide respective electrically conductive paths between the inner electrical contacts **524** and the depletion region formed along the PN junction within the rib ring **507**. Also, along the rib ring **507** between the optical coupling regions **520** and **570**, the N-type doping regions **527** formed within the partial-height (partial-thickness) silicon region **517** provide electrically conductive paths between the inner electrical contacts **523** and the depletion region formed along the PN junction within the rib ring **507**. Also, along the rib ring **507** between of the optical coupling regions **520** and **570**, the P-type doped spoke regions **529**S formed within the partial-height (partial-thickness) silicon region **517** provide electrically conductive paths between the inner electrical contacts **524** and the depletion region formed along the PN junction within the rib ring **507**.

[0156] In some embodiments, with the lateral PN junction diode within the rib ring **507** electrically connected in a reverse-biased manner to an electrical voltage source, the inner electrical contacts **523** of the N-type doping regions **527** are electrically connected to the anode of the electrical voltage source by way of the electrical conductor **581**. Also, in some embodiments, with the lateral PN junction diode within the rib ring **507** electrically connected in a reverse-biased manner to the electrical voltage source, the inner electrical contacts **524** of the P-type doping region **529** are electrically connected to the cathode of the electrical voltage source. The inner electrical contacts **523** and **524** are positioned far enough from the rib ring **507** to reduce optical absorption of the light traveling through the rib ring **507** by metal and silicided regions that form the inner electrical contacts **523** and **524**.

[0157] In the ring modulator **500**, the lateral PN junction diode extends into the optical coupling region **520** of the ring modulator **500** without adversely affecting optical absorption loss in the optical waveguide **513** to which the ring modulator **500** is optically coupled. Also, positioning of the N-type doping regions **527** and the P-type doped spoke regions **529**S on the inside of the rib ring **507** so as to extend toward the center **540** of ring modulator **500** enables the lateral PN junction diode to extend through the optical coupling region **520** of the ring modulator **500** without adversely affecting optical absorption loss in the optical waveguide **513** to which the ring modulator **500** is optically coupled. Additionally, by having the N-type doping regions **527** and the P-type doped spoke regions **529**S alternatively positioned along the arc of the rib ring **507** within the optical coupling region **520**, the electrical series resistance in the lateral PN junction diode of the ring modulator **500** is not adversely increased by having the lateral PN junction diode extend through the optical coupling region **520**.

[0158] In the ring modulator **500**, the lateral PN junction diode extends into the optical coupling region **570** of the ring modulator **500** without adversely affecting optical absorption loss in the optical waveguide **563** to which the ring modulator **500** is optically coupled. Also, positioning of the N-type doping regions **527** and the P-type doped spoke regions **529**S on the inside of the rib ring **507** so as to extend toward the center **540** of ring modulator **500** enables the lateral PN junction diode to extend through the optical coupling region **570** of the ring modulator **500** without adversely affecting optical absorption loss in the optical waveguide **563** to which the ring modulator **500** is optically coupled. Additionally, by having the N-type doping regions **527** and P-type doped spoke regions **529**S alternatively positioned along the arc of the rib ring **507** within the optical coupling region **570**, the electrical series resistance in the lateral PN junction diode of the ring modulator **500** is not adversely increased by having the lateral PN junction diode extend through the optical coupling region **570**.

[0159] The ring modulator **500** uses the circuitous interdigitated PN junction diode design (interdigitation of the N-type doping regions **527** and P-type doped spoke regions **529**S) around the entirety of the rib ring **507**, including through portions of the rib ring **507** that pass through each of the optical coupling regions **520** and **570**. Within the optical coupling region **520**, the inner electrical contacts **523** and **524** are positioned along the inner region of the ring modulator **500**, far from the rib ring **507** and even farther from the optical waveguide **513**, so as to avoid optical absorption loss in the coupling optical waveguides **507** and **513**. Similarly, within the optical coupling region **570**, the inner electrical contacts **523** and **524** are positioned along the inner region of the ring modulator **500**, far from the rib ring **507** and even farther from the optical waveguide **563**, so as to avoid optical absorption loss in the coupling optical waveguides **507** and **563**. The circuitous interdigitated N-type doping regions **527** and the P-type doped spoke regions **529**S alternate polarity (alternate cathode and anode) around the rib ring **507**, including through each of the optical coupling regions **520** and **570**.

[0160] In various embodiments, electrically conductive structures, e.g., metal traces/wires, and electrically conductive via structures are formed in and/or through different levels of the semiconductor device in which the ring modulator **500** is formed in order to electrically connect all of the inner electrical contacts **523** that are electrically connected to the N-type doping regions **527** to the same first electrical node, such as exemplified by the electrical conductor **581**. In various embodiments, electrically conductive structures, e.g., metal traces/wires, and electrically conductive via structures are formed in and/or through different levels of the semiconductor device in which the ring modulator **500** is formed in order to electrically connect all of the inner electrical contacts **524** that are electrically connected to the P-type doping region **529** to the same second electrical node, such as exemplified by the electrical conductor **583**.

[0161] In accordance with the foregoing, the ring resonator **500** includes a built-in diode for modulating an optical signal propagating through the optical waveguide **513** and/or the optical waveguide **563**. The optical mode supported by the ring resonator **500** has significant power density that overlaps the depletion region of the PN junction diode within the rib ring **507**. By changing the voltage differential between the anode and cathode of the PN junction diode within the rib ring **507**, charge carriers can be added to or removed from the depletion region of the PN junction within the rib ring **507** in a controlled manner, which provides for changing of the refractive index and optical absorption coefficient of the rib ring **507** in a controlled manner by way of the plasma effect, which in turn provides for changing of the amplitude and phase of the light that is transmitted on through the optical waveguide **513** and/or the optical waveguide **563** past the ring modulator **500** in a controlled manner. In some embodiments, the PN junction diode within the rib ring **507** of the ring modulator **500** is operated in a reversed bias manner to enable fast charge transport and correspondingly high optical modulation data rates.

[0162] In some embodiments, the optical waveguide **513** and/or the optical waveguide **563** carries multiple wavelength channels of light, where only one of the multiple wavelength channels of light is coupled into and modulated by the ring resonator **500** in a controlled and selectable manner. In some embodiments, such as in WDM systems, multiple instances of the ring resonator **500** are optically coupled to the same optical waveguide **513** and/or the optical waveguide **563**, with each of the ring resonators **500** tuned to modulate a different one of the multiple wavelength channels of light propagating through the optical waveguide **513** and/or the optical waveguide **563**. The metal of the inner electrical contacts **523** and **524** absorbs light across all wavelengths. Therefore, by having the inner electrical contacts **523** and **524** positioned away from the optical waveguides **513** and **563**, e.g., by a distance greater than or equal to about one micrometer, within each instance of the ring modulator **500**, it is possible to avoid introduction and accumulation of excess absorption loss of the light propagating through the optical waveguides **513** and **563**, across every wavelength channel of light. Also, by having the contacts **523** and **524** positioned on the inner radius of the ring modulator **500**, the area along the outer radius of the ring modulator **500** is available for positioning of one or more heating device(s), e.g., resistive heating device(s), to provide for thermal resonance wavelength tuning of the ring resonator **500**. In some embodiments, doped or silicided silicon is used to form one or more resistive heating device (s) along the outer radius of the ring modulator **500**, such as along the full-height (full-thickness) silicon regions **505** and **506**.

[0163] FIGS. **5**A through **5**H show a portion of a photonic integrated circuit. The photonic integrated circuit includes a first optical waveguide **507** that has a ring shape. The first optical waveguide **507** is formed of silicon and has a first vertical height. The photonic integrated circuit also includes an inner silicon region **517** formed circumferentially along an inner side of the first optical waveguide **507**. The inner silicon region **517** has a second vertical height that is less than the first vertical height of the first optical waveguide **507**. The photonic integrated circuit also includes a second optical waveguide **513** configured to semi-tangentially approach an outer side of the first optical waveguide **507** and extend past the first optical waveguide **507** at a first location (of closest approach), such that a first optical coupling region **520** exists between a portion of the second optical waveguide **513** and a first portion of the first optical waveguide **507** about the first location (of closest approach). The photonic integrated circuit also includes a third optical waveguide **563** configured to semi-tangentially approach the outer side of the first optical waveguide **507** and extend past the first optical waveguide **507** at a second location (of closest approach) that is diametrically opposed to the first location (of closest approach) with regard to the ring shape of the first optical waveguide **507**, such that a second optical coupling region **570** exists between a portion of the third optical waveguide **563** and a second portion of the first optical waveguide **507** about the second location (of closest approach).

[0164] The photonic integrated circuit also includes an N-type doping region **527** formed within the first optical waveguide **507** and the inner silicon region **517**. The N-type doping region **527** includes multiple tab-shaped N-type doping regions **527** formed within the first optical waveguide **507** and the inner silicon region **517**. The multiple tab-shaped N-type doping regions **527** are positioned in a spaced apart manner along a full circumferential path of the ring shape of the first optical waveguide **507**. Each of the multiple tab-shaped N-type doping regions **527** is formed to project inward toward a center **540** of the ring shape of the first optical waveguide **507**.

[0165] The photonic integrated circuit also includes a P-type doping region **529** formed within the first optical waveguide **507** and the inner silicon region **517**. The P-type doping region **529** includes multiple tab-shaped P-type doping regions **529S** formed within the first optical waveguide **507** and the inner silicon region **517**. Each of the multiple tab-shaped P-type doping regions **529S** is positioned between a different pair of the multiple tab-shaped N-type doping regions **527** along the full circumferential path of the ring shape of the first optical waveguide **507**. Each of the multiple tab-shaped P-type doping regions **529S** is formed to project inward toward the center **540** of the ring shape of the first optical waveguide **507**. The multiple tab-shaped N-type doping regions **527** and the multiple tab-shaped P-type doping regions **529S** collectively form an interdigitated PN diode configuration within the first optical waveguide **507** along the full circumferential path of the ring shape of the first optical waveguide **507**. A first portion of the interdigitated PN diode configuration is positioned within the first optical coupling region **520**. A second portion of the interdigitated PN diode configuration is positioned within the second optical coupling region **570**. A third portion of the interdigitated PN diode configuration is positioned between the first optical coupling region **520** and the second optical coupling region **570** on a first side of the center **540** of the ring shape of the first optical waveguide **507**. A fourth portion of the interdigitated PN diode configuration is positioned between the first optical coupling region **520** and the second optical coupling region **570** on a second side of the center **540** of the ring shape of the first optical waveguide **507**.

[0166] The P-type doping region **529** includes a connecting portion **529**R that is contiguously formed along the full circumferential path of the ring shape of the first optical waveguide **507**. The connection portion **529**R of the P-type doping region **529** is contiguously formed with each of the multiple tab-shaped P-type doping regions **529**S. Adjacently positioned ones of the multiple tab-shaped N-type doping regions **527** and the multiple tab-shaped P-type doping regions **529**S are physically separated from each other. Each of the multiple tab-shaped N-type doping regions **527** is in physical contact with the connecting portion **529**R of the P-type doping region **529** within the first optical waveguide **507**. The connecting portion **529**R of the P-type doping region **529** extends along an outer side of each of the multiple tab-shaped N-type doping regions **527**.

[0167] The photonic integrated circuit also includes multiple inner electrical contacts **523** respectively physically connected to each of the multiple tab-shaped N-type doping regions **527**. The photonic integrated circuit also includes multiple inner electrical contacts **524** respectively physically connected to each of the multiple tab-shaped P-type doping regions **529**S. Each of the multiple inner electrical contacts **523** and **524** is positioned at an inner edge of the inner silicon region **517** relative to the center **540** of the ring shape of the first optical waveguide **507**. In some embodiments, the multiple tab-shaped N-type doping regions **527** are electrically connected to a first electrical node by way of corresponding ones of the multiple inner electrical contacts **523**. Also, the multiple tab-shaped P-type doping regions **529**S are electrically connected to a second electrical node by way of corresponding ones of the multiple inner electrical contacts **524**. The second electrical node is electrically separated from the first electrical node. In some embodiments, the first electrical node is electrically connected to an anode of an electrical voltage source, and the second electrical node is electrically connected to a cathode of the electrical voltage source, such that the interdigitated PN diode configuration is reverse-biased.

[0168] The photonic integrated circuit also includes an outer silicon region **519** formed circumferentially along the outer side of the first optical waveguide **507**. The outer silicon region **519** is not doped. The outer silicon region **519** is formed between the first optical waveguide **507** and the second optical waveguide **513**. The outer silicon region **519** is also formed between the first optical waveguide **507** and the third optical waveguide **563**. The outer silicon region **519** has a third vertical height that is less than the first vertical height of the first optical waveguide **507**. In some embodiments, the third vertical height of the outer silicon region **519** is substantially equal to the second vertical height of the inner silicon region **517**. In some embodiments, a vertical height of the second optical waveguide **513** is substantially equal to the first vertical height of the first optical waveguide **507**.

[0169] In some embodiments, the first optical waveguide **507**, the second optical waveguide **513**, the third optical waveguide **563**, the outer silicon region **519**, and the inner silicon region **517** are respective parts of a contiguous silicon structure. In some embodiments, the contiguous silicon structure has a planar bottom surface that forms a respective bottom surface of each of the first optical waveguide **507**, the second optical waveguide **513**, the third optical waveguide **563**, the outer silicon region **519**, and the inner silicon region **517**. In some embodiments, the outer silicon region **519** and the inner silicon region **517** are etched regions of the contiguous silicon structure.

[0170] In some embodiments, each of the multiple tab-shaped N-type doping regions **527** is substantially T-shaped, and wherein each of the multiple tab-shaped P-type doping regions **529**S is substantially linear-shaped. In some embodiments, the multiple tab-shaped N-type doping regions **527** are substantially uniformly azimuthally spaced about the center **540** of the ring shape of the first optical waveguide **507**, and the multiple tab-shaped P-type doping regions **529**S are substantially uniformly azimuthally spaced about the center **540** of the ring shape of the first optical waveguide **507**.

[0171] Various configurations of ring modulators are disclosed herein that include a rib ring optical waveguide and an interdigitated PN junction diode design that extend through an optical coupling region between the rib ring optical waveguides and a proximally positioned bus optical waveguide. The implementation of the interdigitated PN junction diode design in conjunction with the rib ring optical waveguide provides for optimization of the modulation efficiency of the ring modulator while minimizing loss in the rib ring optical waveguide and the bus optical waveguide that is coupled to the ring modulator. The interdigitated PN junction diode design has electrical contacts of alternating polarity along the inner ring radius of the ring modulator in those parts of the ring modulator that are within and/or near the optical coupling region between the ring modulator and the bus optical waveguide, which avoids placement of metal contacts and associated wiring of the ring modulator in positions that would contribute to excess optical absorption loss of light propagating through the bus optical waveguide that is optically coupled to the ring modulator. The various ring modulator embodiments disclosed herein provide for high modulation efficiency, which is particularly beneficial in systems that use wavelength division multiplexing (WDM), especially where multiple ring modulators are coupled to the same bus optical waveguide to enable optical data communication on multiple optical wavelength channels in a simultaneous manner.

[0172] The foregoing description of the embodiments has been provided for purposes of illustration and description, and is not intended to be exhaustive or limiting. Individual elements or features of a particular embodiment are generally not limited to that particular embodiment, but, where applicable, are interchangeable and can be used in a selected embodiment, even if not specifically shown or described. In this manner, one or more features from one or more embodiments disclosed herein can be combined with one or more features from one or more other embodiments disclosed herein to form another embodiment that is not explicitly disclosed herein, but rather that is implicitly disclosed herein. This other embodiment may also be varied in many ways. Such embodiment variations are not to be regarded as a departure from the disclosure herein, and all such embodiment variations and modifications are intended to be included within the scope of the disclosure provided herein.

[0173] Although some method operations may be described in a specific order herein, it should be understood that other operations may be performed in between method operations, and/or method operations may be adjusted so that they occur at slightly different times or simultaneously, or may be distributed in a system which allows the occurrence of the processing operations at various intervals associated with the processing, as long as the processing of the method operations are performed in a manner that provides for successful implementation of the method.

[0174] Although the foregoing embodiments have been described in some detail for purposes of clarity of understanding, it will be apparent that certain changes and modifications can be practiced within the scope of the appended claims. Accordingly, the embodiments disclosed herein are to be considered as illustrative and not restrictive, and are therefore not to be limited to just the details given herein, but may be modified within the scope and equivalents of the appended claims.

What is claimed is:

1. A photonic integrated circuit, comprising:

a first optical waveguide having a ring shape, the first optical waveguide formed of silicon and having a first vertical height;

an inner silicon region formed circumferentially along an inner side of the first optical waveguide, the inner silicon region having a second vertical height that is less than the first vertical height;

a second optical waveguide configured to semi-tangentially approach an outer side of the first optical waveguide and extend past the first optical waveguide at a first location, such that a first optical coupling region exists between a portion of the second optical waveguide and a first portion of the first optical waveguide about the first location;

a third optical waveguide configured to semi-tangentially approach the outer side of the first optical waveguide and extend past the first optical waveguide at a second location that is diametrically opposed to the first location with regard to the ring shape of the first optical waveguide, such that a second optical coupling region exists between a portion of the third optical waveguide and a second portion of the first optical waveguide about the second location;

an N-type doping region formed within the first optical waveguide and the inner silicon region, the N-type doping region including a first set of multiple tab-shaped N-type doping regions formed within the first optical coupling region, the N-type doping region including a second set of multiple tab-shaped N-type doping regions formed within the second optical coupling region, each of the tab-shaped N-type doping regions in the first and second sets of multiple tab-shaped N-type doping regions formed to project inward toward a center of the ring shape of the first optical waveguide; and

a P-type doping region formed within the first optical waveguide and the inner silicon region, the P-type doping region including a first set of multiple tab-shaped P-type doping regions formed within the first optical coupling region, the P-type doping region including a second set of multiple tab-shaped P-type doping regions formed within the second optical coupling region, each of the tab-shaped P-type doping regions in the first and second sets of multiple tab-shaped P-type doping regions formed to project inward toward the center of the ring shape of the first optical waveguide,

wherein positions of the first set of multiple tab-shaped N-type doping regions alternate with positions of the first set of multiple tab-shaped P-type doping regions along the first portion of the first optical waveguide, such that the first set of multiple tab-shaped N-type doping regions and the first set of multiple tab-shaped P-type doping regions collectively form a first interdigitated PN diode configuration within the first optical waveguide within the first optical coupling region,

wherein positions of the second set of multiple tab-shaped N-type doping regions alternate with positions of the second set of multiple tab-shaped P-type doping regions along the second portion of the first optical waveguide, such that the second set of multiple tab-shaped N-type doping regions and the second set of multiple tab-shaped P-type doping regions collectively form a second interdigitated PN diode configuration within the first optical waveguide within the second optical coupling region.

2. The photonic integrated circuit as recited in claim **1**, wherein the N-type doping region includes a first connecting portion that is formed within the first optical waveguide through the first optical coupling region and that is contiguously formed with each of the first set of multiple tab-shaped N-type doping regions,

wherein the P-type doping region includes a first connecting portion that is formed within the first optical waveguide through the first optical coupling region and that is contiguously formed with each of the first set of multiple tab-shaped P-type doping regions,

wherein the N-type doping region includes a second connecting portion that is formed within the first optical waveguide through the second optical coupling region and that is contiguously formed with each of the second set of multiple tab-shaped N-type doping regions, and

wherein the P-type doping region includes a second connecting portion that is formed within the first optical waveguide through the second optical coupling region and that is contiguously formed with each of the second set of multiple tab-shaped P-type doping regions.

3. The photonic integrated circuit as recited in claim **2**, wherein adjacently positioned ones of the first set of multiple tab-shaped N-type doping regions and the first set of multiple tab-shaped P-type doping regions are physically separated from each other, and wherein adjacently positioned ones of the second set of multiple tab-shaped N-type doping regions and the second set of multiple tab-shaped P-type doping regions are physically separated from each other.

4. The photonic integrated circuit as recited in claim **3**, wherein the first connecting portion of the N-type doping region is in physical contact with the first connecting portion of the P-type doping region within the first optical waveguide, and wherein the second connecting portion of the N-type doping region is in physical contact with the second connecting portion of the P-type doping region within the first optical waveguide.

5. The photonic integrated circuit as recited in claim **4**, wherein the first connecting portion of the P-type doping region extends below the first connecting portion of the N-type doping region, and wherein the second connecting portion of the P-type doping region extends below the second connecting portion of the N-type doping region.

6. The photonic integrated circuit as recited in claim **5**, wherein the first connecting portion of the N-type doping region is circumscribed by an annular segment of the first connecting portion of the P-type doping region, and wherein the second connecting portion of the N-type doping region is circumscribed by an annular segment of the second connecting portion of the P-type doping region.

7. The photonic integrated circuit as recited in claim **4**, further comprising:

a first set of multiple inner electrical contacts respectively physically connected to each of the first set of multiple tab-shaped N-type doping regions and each of the first set of multiple tab-shaped P-type doping regions; and

a second set of multiple inner electrical contacts respectively physically connected to each of the second set of multiple tab-shaped N-type doping regions and each of the second set of multiple tab-shaped P-type doping regions.

8. The photonic integrated circuit as recited in claim **7**, wherein each of the first set of multiple inner electrical contacts and each of the second set of multiple inner electrical contacts is positioned at an inner edge of the inner silicon region relative to the center of the ring shape of the first optical waveguide.

9. The photonic integrated circuit as recited in claim **7**, wherein the first set of multiple tab-shaped N-type doping regions are electrically connected to a first electrical node by way of corresponding ones of the first set of multiple inner electrical contacts, wherein the first set of multiple tab-shaped P-type doping regions are electrically connected to a second electrical node by way of corresponding ones of the first set of multiple inner electrical contacts, the second electrical node electrically separated from the first electrical node, and

wherein the second set of multiple tab-shaped N-type doping regions are electrically connected to a third electrical node by way of corresponding ones of the second set of multiple inner electrical contacts, wherein the second set of multiple tab-shaped P-type doping regions are electrically connected to a fourth electrical node by way of corresponding ones of the second set of multiple inner electrical contacts, the fourth electrical node electrically separated from the third electrical node.

10. The photonic integrated circuit as recited in claim **9**, wherein the first electrical node is electrically connected to an anode of a first electrical voltage source, and wherein the second electrical node is electrically connected to a cathode of the first electrical voltage source, such that the first interdigitated PN diode configuration is reverse-biased, and

wherein the third electrical node is electrically connected to an anode of a second electrical voltage source, and wherein the fourth electrical node is electrically connected to a cathode of the second electrical voltage source, such that the second interdigitated PN diode configuration is reverse-biased.

11. The photonic integrated circuit as recited in claim **4**, further comprising:

an outer silicon region formed circumferentially along the outer side of the first optical waveguide, the outer silicon region formed between the first optical waveguide and the second optical waveguide, the outer silicon region also formed between the first optical waveguide and the third optical waveguide, the outer silicon region having a third vertical height that is less than the first vertical height.

12. The photonic integrated circuit as recited in claim **11**, wherein the third vertical height is substantially equal to the second vertical height.

13. The photonic integrated circuit as recited in claim **12**, wherein a vertical height of the second optical waveguide is substantially equal to the first vertical height of the first optical waveguide, and wherein a vertical height of the third optical waveguide is substantially equal to the first vertical height of the first optical waveguide.

14. The photonic integrated circuit as recited in claim **11**, wherein the outer silicon region is not doped.

15. The photonic integrated circuit as recited in claim **14**, wherein the first optical waveguide, the second optical waveguide, the third optical waveguide, the outer silicon region, and the inner silicon region are respective parts of a contiguous silicon structure.

16. The photonic integrated circuit as recited in claim **15**, wherein the contiguous silicon structure has a planar bottom surface that forms a respective bottom surface of each of the first optical waveguide, the second optical waveguide, the third optical waveguide, the outer silicon region, and the inner silicon region.

17. The photonic integrated circuit as recited in claim **16**, wherein the outer silicon region and the inner silicon region are etched regions of the contiguous silicon structure.

18. The photonic integrated circuit as recited in claim **11**, wherein the N-type doping region includes a first central portion that is contiguously formed within the inner silicon region along a first azimuthal angular span about the center of the ring shape of the first optical waveguide between the first and second interdigitated PN diode configurations, and wherein the P-type doping region includes a first central portion that is contiguously formed within the outer silicon region along the first azimuthal angular span,

wherein the N-type doping region includes a second central portion that is contiguously formed within the inner silicon region along a second azimuthal angular span about the center of the ring shape of the first optical waveguide between the first and second interdigitated PN diode configurations, and wherein the P-type doping region includes a second central portion that is contiguously formed within the outer silicon region along the second azimuthal angular span, wherein a location of the second azimuthal angular span is diametrically opposed to a location of the first azimuthal angular span with regard to the ring shape of the first optical waveguide.

19. The photonic integrated circuit as recited in claim **18**, wherein the first central portion of the N-type doping region and the first central portion of the P-type doping region interface with each other to form a first continuous PN diode configuration within the first optical waveguide along the first azimuthal angular span, and

wherein the second central portion of the N-type doping region and the second central portion of the P-type doping region interface with each other to form a second continuous PN diode configuration within the first optical waveguide along the second azimuthal angular span.

20. The photonic integrated circuit as recited in claim **19**, wherein an interface between the first central portion of the N-type doping region and the first central portion of the P-type doping region has a serpentine configuration along the first azimuthal angular span, and wherein an interface between the second central portion of the N-type doping region and the second central portion of the P-type doping region has a serpentine configuration along the second azimuthal angular span.

21. The photonic integrated circuit as recited in claim **19**, further comprising:

a first set of multiple electrical contacts respectively physically connected to each of the first set of multiple tab-shaped N-type doping regions and each of the first set of multiple tab-shaped P-type doping regions, wherein each electrical contact of the first set of multiple electrical contacts is positioned at an inner edge of the inner silicon region relative to the center of the ring shape of the first optical waveguide, wherein the first set of multiple tab-shaped N-type doping regions are electrically connected to a first electrical node by way of corresponding ones of the first set of multiple electrical contacts, wherein the first set of multiple tab-shaped P-type doping regions are electrically connected to a second electrical node by way of corresponding ones of the first set of multiple electrical contacts, wherein the first electrical node is electrically connected to an anode of a first electrical voltage source, and wherein the second electrical node is electrically connected to a cathode of the first electrical voltage source, such that the first interdigitated PN diode configuration is reverse-biased;

a second set of multiple electrical contacts respectively physically connected to each of the second set of multiple tab-shaped N-type doping regions and each of the second set of multiple tab-shaped P-type doping regions, wherein each electrical contact of the second set of multiple electrical contacts is positioned at an inner edge of the inner silicon region relative to the center of the ring shape of the first optical waveguide, wherein the second set of multiple tab-shaped N-type doping regions are electrically connected to a third electrical node by way of corresponding ones of the second set of multiple electrical contacts, wherein the second set of multiple tab-shaped P-type doping regions are electrically connected to a fourth electrical node by way of corresponding ones of the second set of multiple electrical contacts, wherein the third electrical node is electrically connected to an anode of a second electrical voltage source, and wherein the fourth electrical node is electrically connected to a cathode of the second electrical voltage source, such that the second interdigitated PN diode configuration is reverse-biased;

a third set of multiple electrical contacts positioned in a spaced apart configuration along an inner edge of the inner silicon region along the first azimuthal angular span between the first and second interdigitated PN diode configurations;

a fourth set of multiple electrical contacts positioned in a spaced apart configuration along an outer edge of the outer silicon region along the first azimuthal angular span between the first and second interdigitated PN diode configurations;

a fifth set of multiple electrical contacts positioned in a spaced apart configuration along an inner edge of the inner silicon region along the second azimuthal angular span between the first and second interdigitated PN diode configurations; and

a sixth set of multiple electrical contacts positioned in a spaced apart configuration along an outer edge of the outer silicon region along the second azimuthal angular span between the first and second interdigitated PN diode configurations.

22. The photonic integrated circuit as recited in claim **21**, wherein the third, fourth, fifth, and sixth sets of multiple electrical contacts are electrically connected to optical modulation circuitry.

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