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(54) **METHODS FOR MANUFACTURING THREE-DIMENSIONAL METAMATERIAL DEVICES WITH PHOTOVOLTAIC BRISTLES**

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(73) Assignee: **Q1 Nanosystems Corporation**, El Dorado Hills, CA (US)

(21) Appl. No.: **13/866,387**

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(63) Continuation-in-part of application No. 13/830,295, filed on Mar. 14, 2013.

Publication Classification

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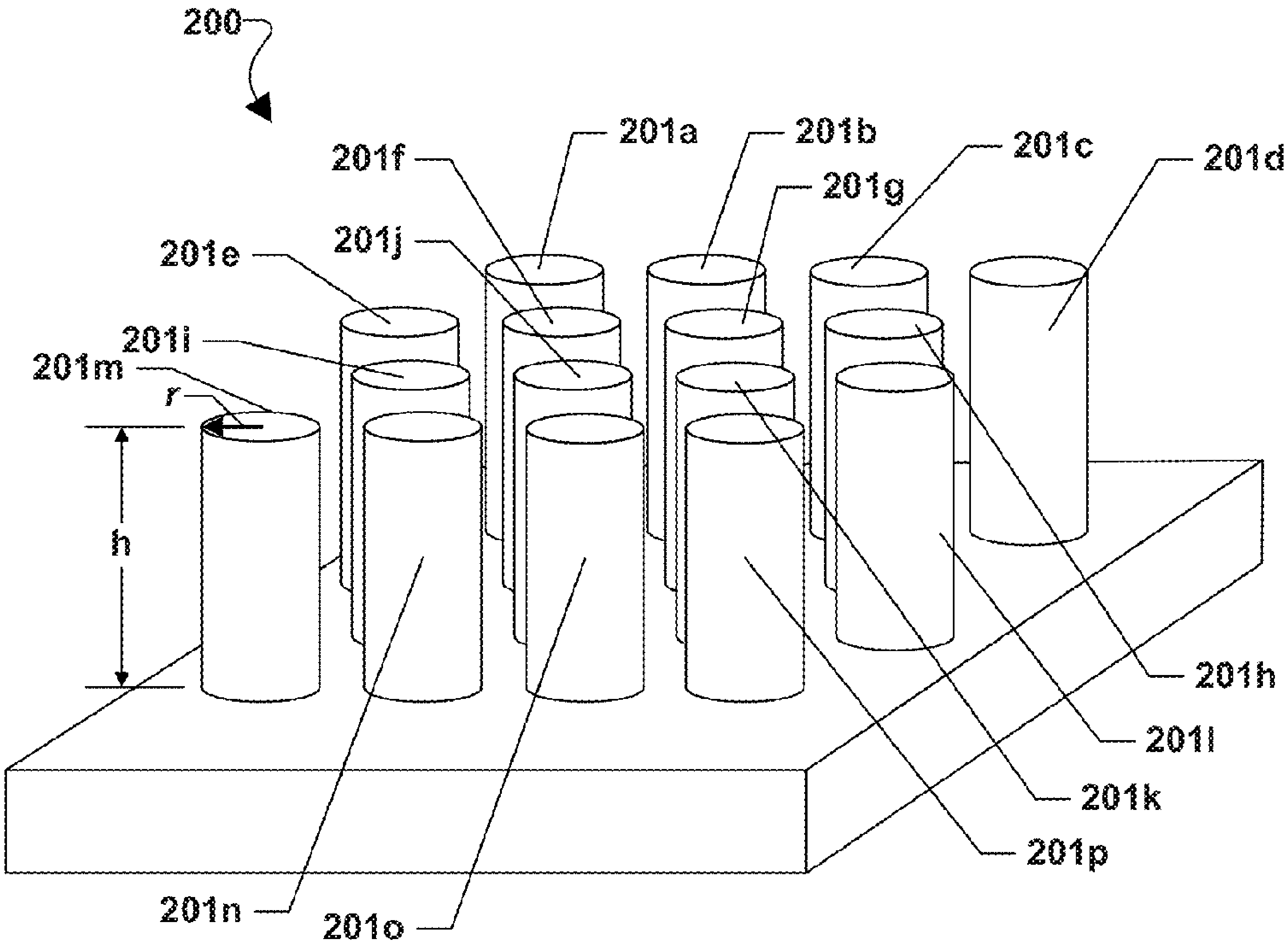
H01L 31/18 (2006.01)

(52) **U.S. Cl.**
CPC ***H01L 31/18*** (2013.01)
USPC **264/104**; 425/175

(57) **ABSTRACT**

Various stamping methods may reduce defects and increase throughput for manufacturing metamaterial devices. Metamaterial devices with an array of photovoltaic bristles, and/or vias, may enable each photovoltaic bristle to have a high probability of photon absorption. The high probability of photon absorption may lead to increased efficiency and more power generation from an array of photovoltaic bristles. Reduced defects in the metamaterial device may decrease manufacturing cost, increase reliability of the metamaterial device, and increase the probability of photon absorption for a metamaterial device. The increase in manufacturing throughput and reduced defects may reduce manufacturing costs to enable the embodiment metamaterial devices to reach grid parity.



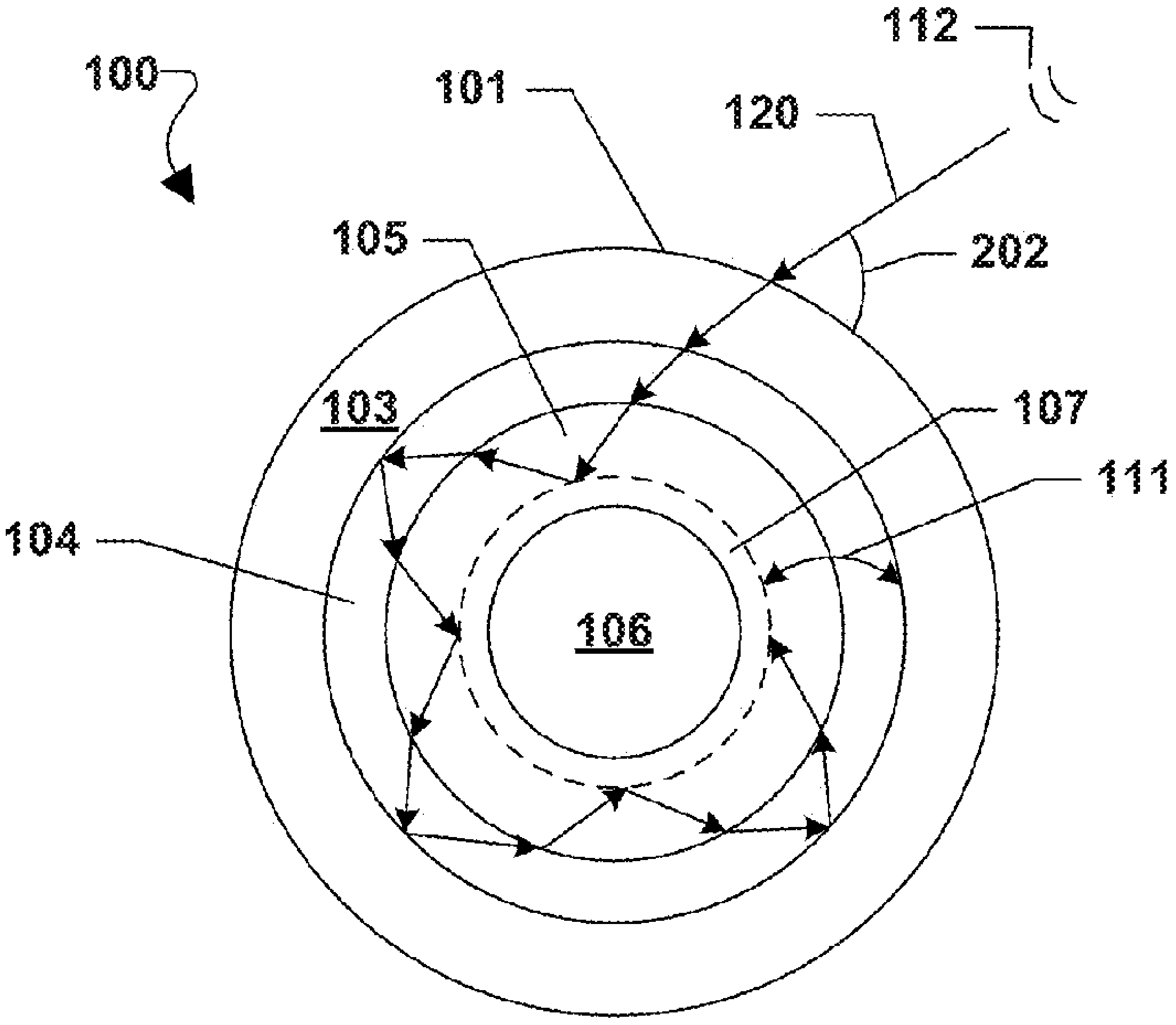

100
101
112
120
202
105
103
107
111
104
106

FIG. 1A

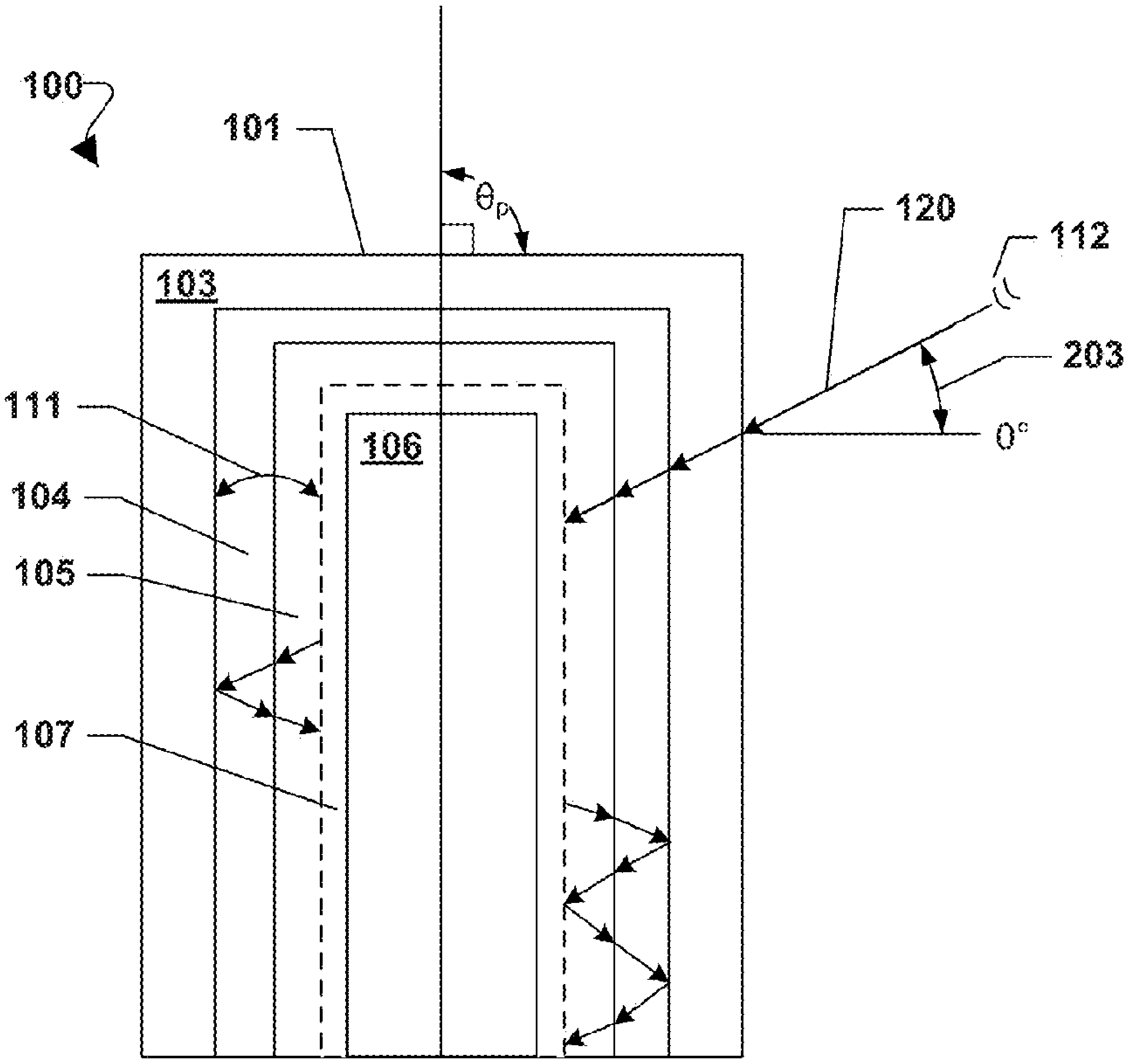

100
101
θ_p
120
112
103
203
0°
111
106
104
105
107

FIG. 1B

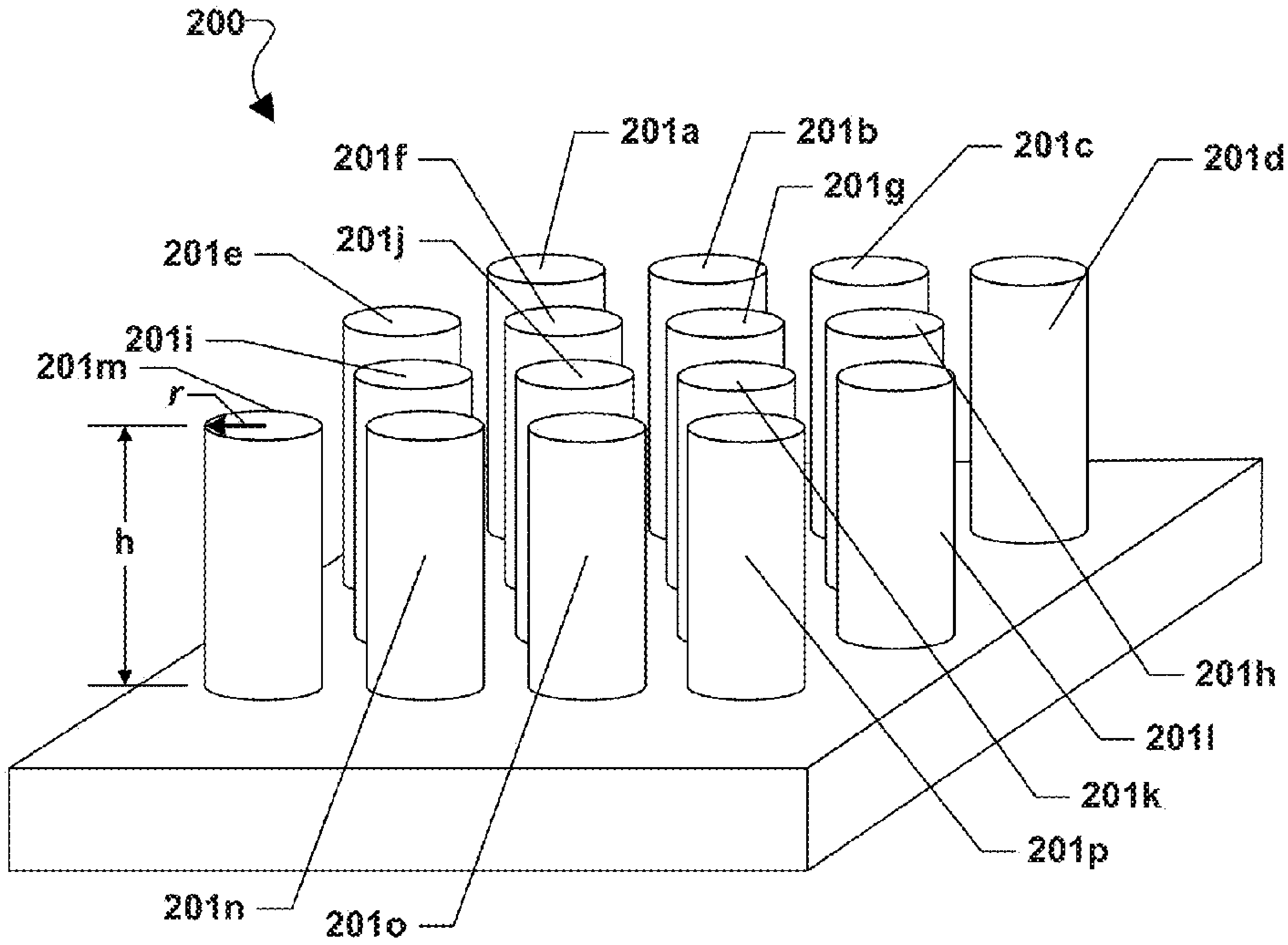
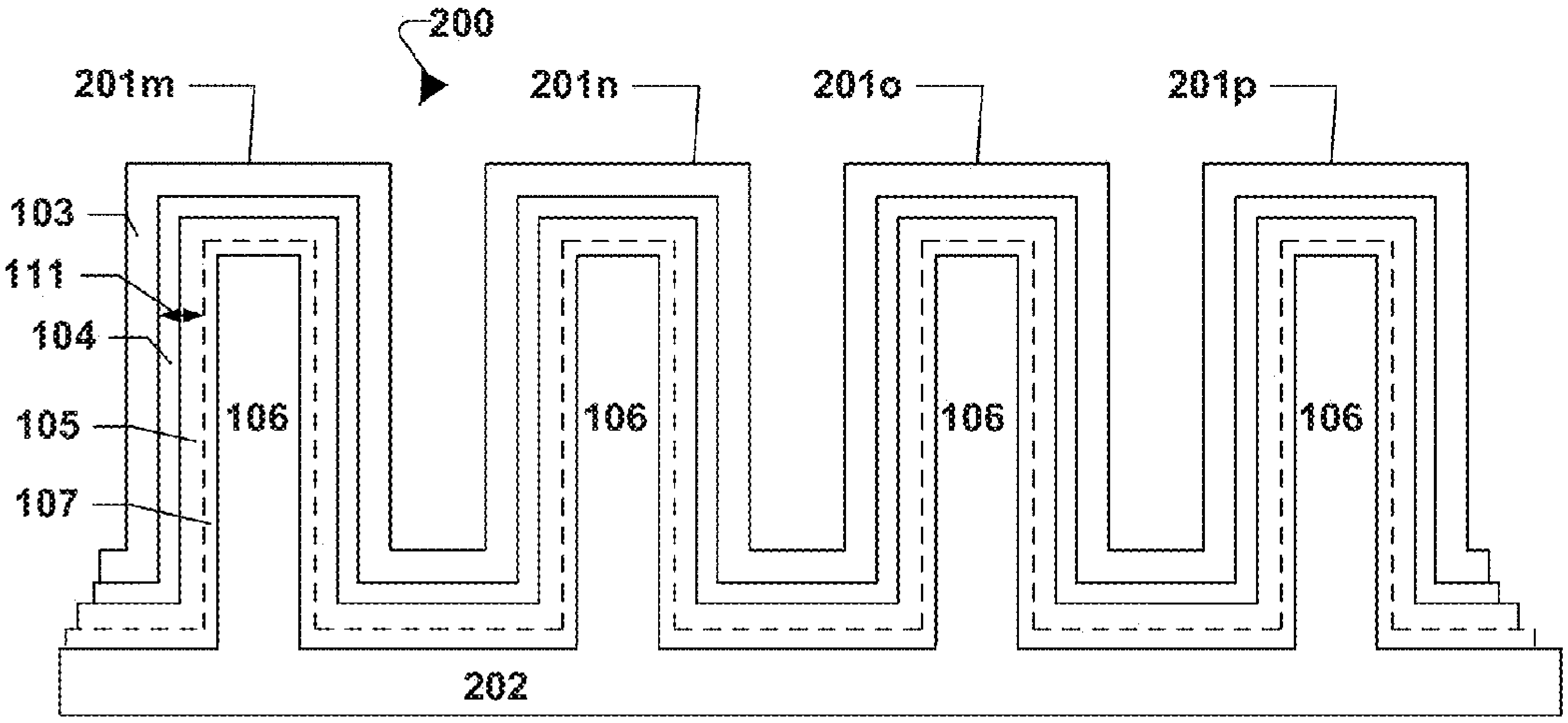

200
201f
201a
201b
201c
201d
201g
201j
201e
201i
201m
r
h
201h
201l
201k
201p
201n
201o

FIG. 2A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201m
201n
201o
201p
103
111
104
105
107
106
106
106
106
202

FIG. 2B

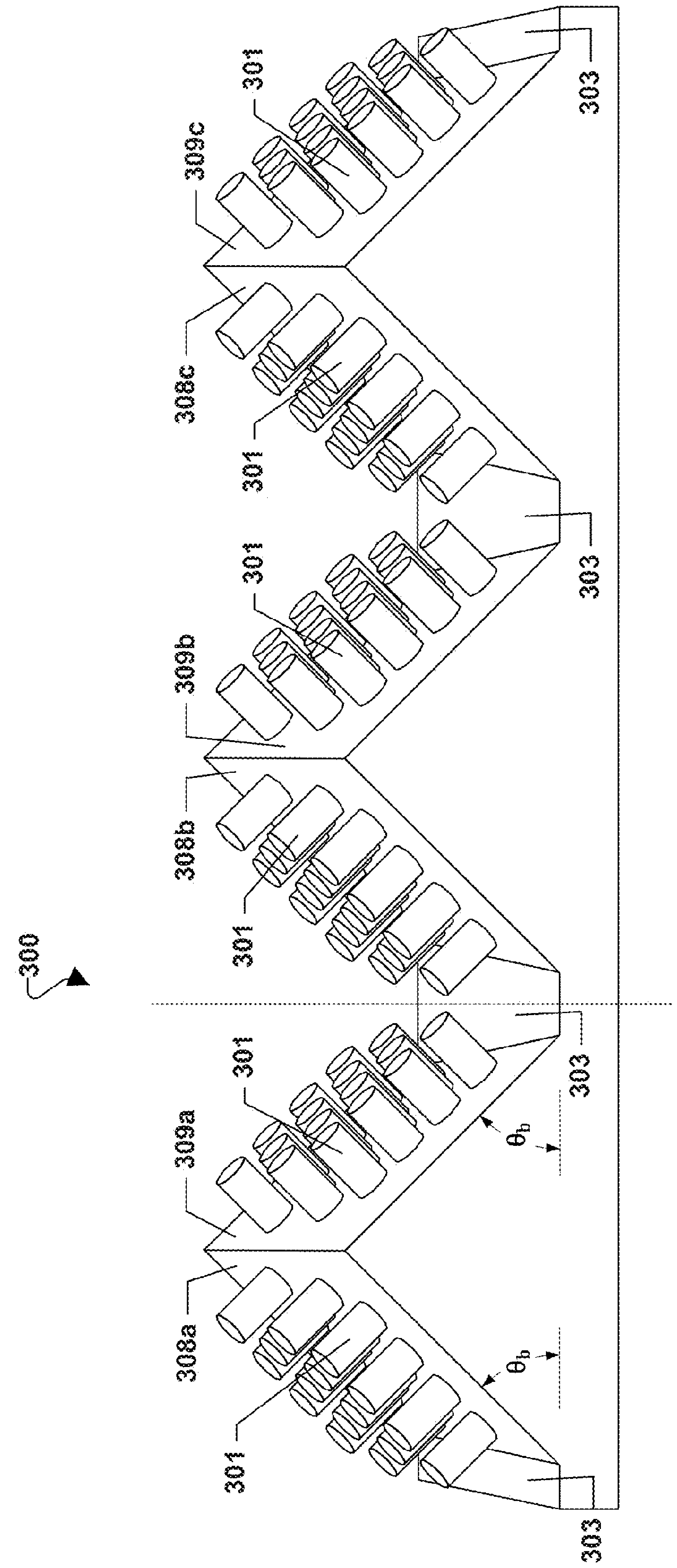
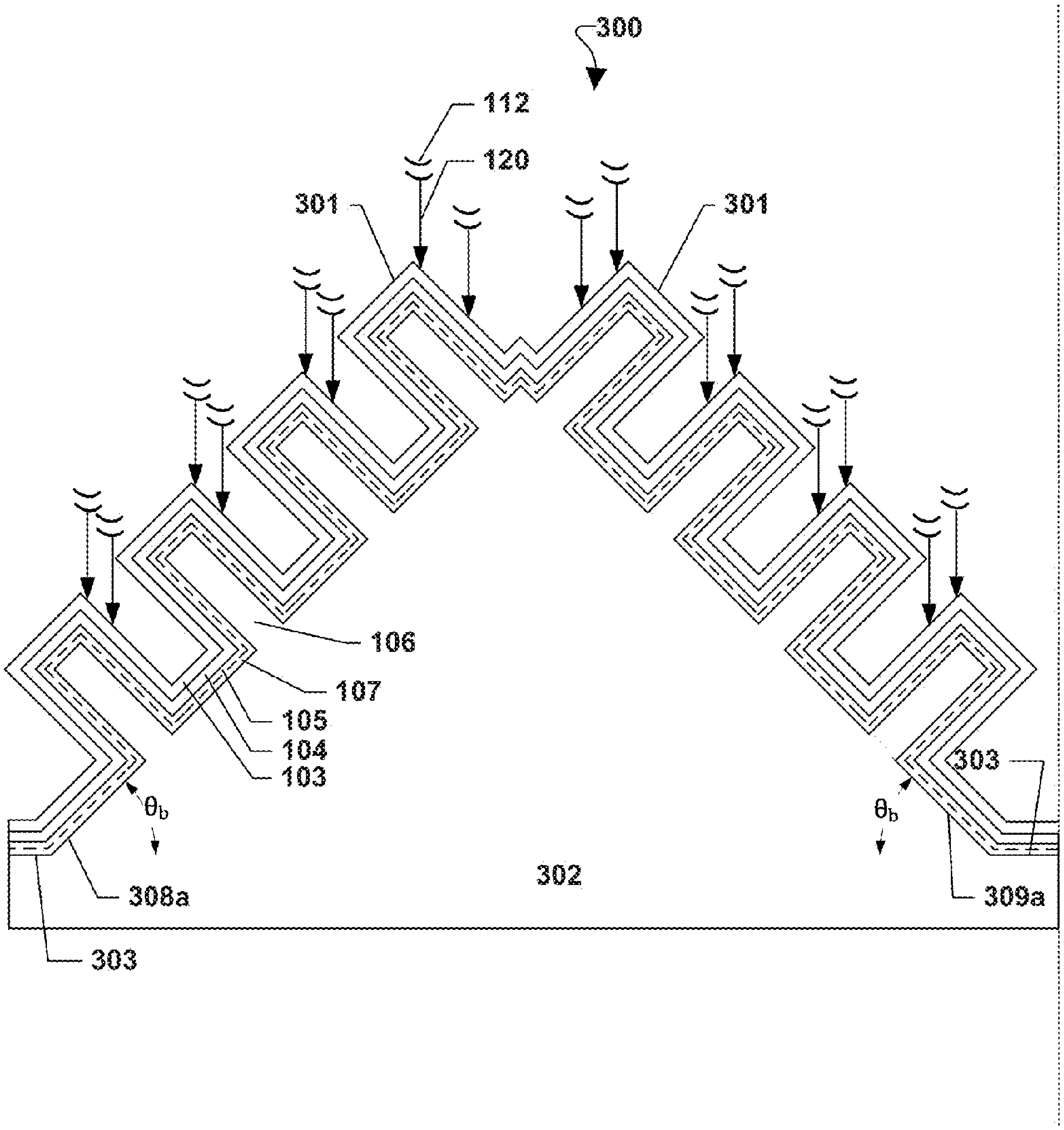

300
308a
301
309a
301
303
θ_b
θ_b
303
308b
301
309b
301
303
308c
301
309c
301
303

FIG. 3A


300
112
120
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301
106
107
105
104
103
θ_b
θ_b
303
303
308a
309a
302

FIG. 3B

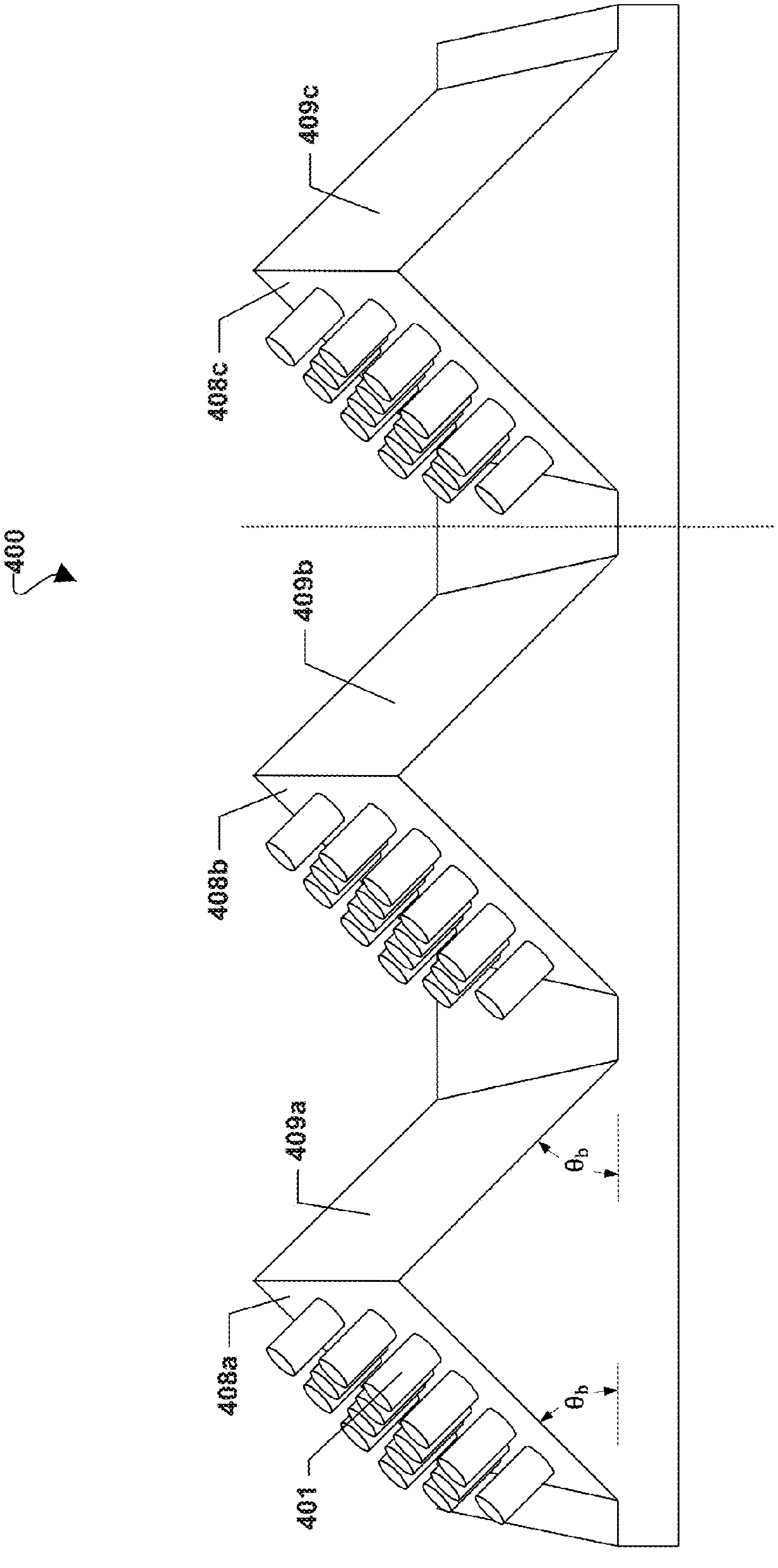

FIG. 4A

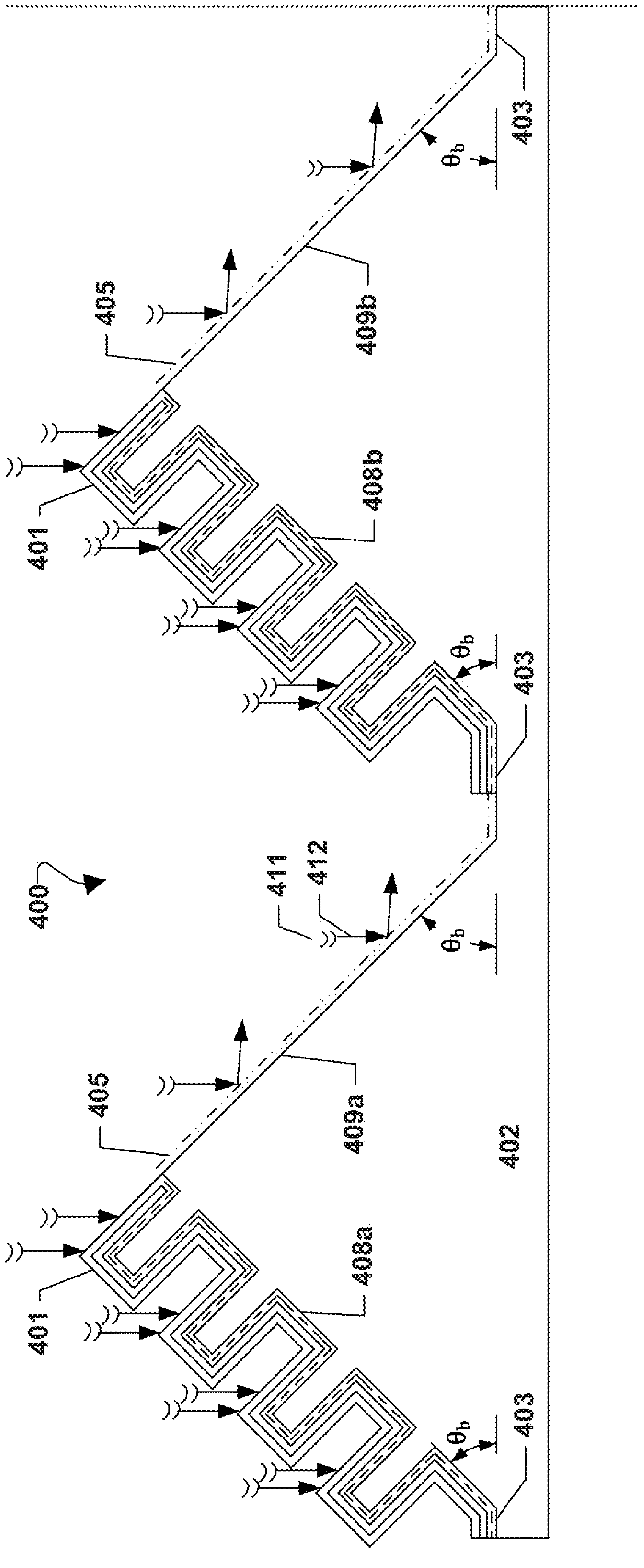
400
401
405
409b
408b
403
θ_b
401
405
409a
408a
411
412
402
403
θ_b
403
θ_b
403
θ_b

FIG. 4B

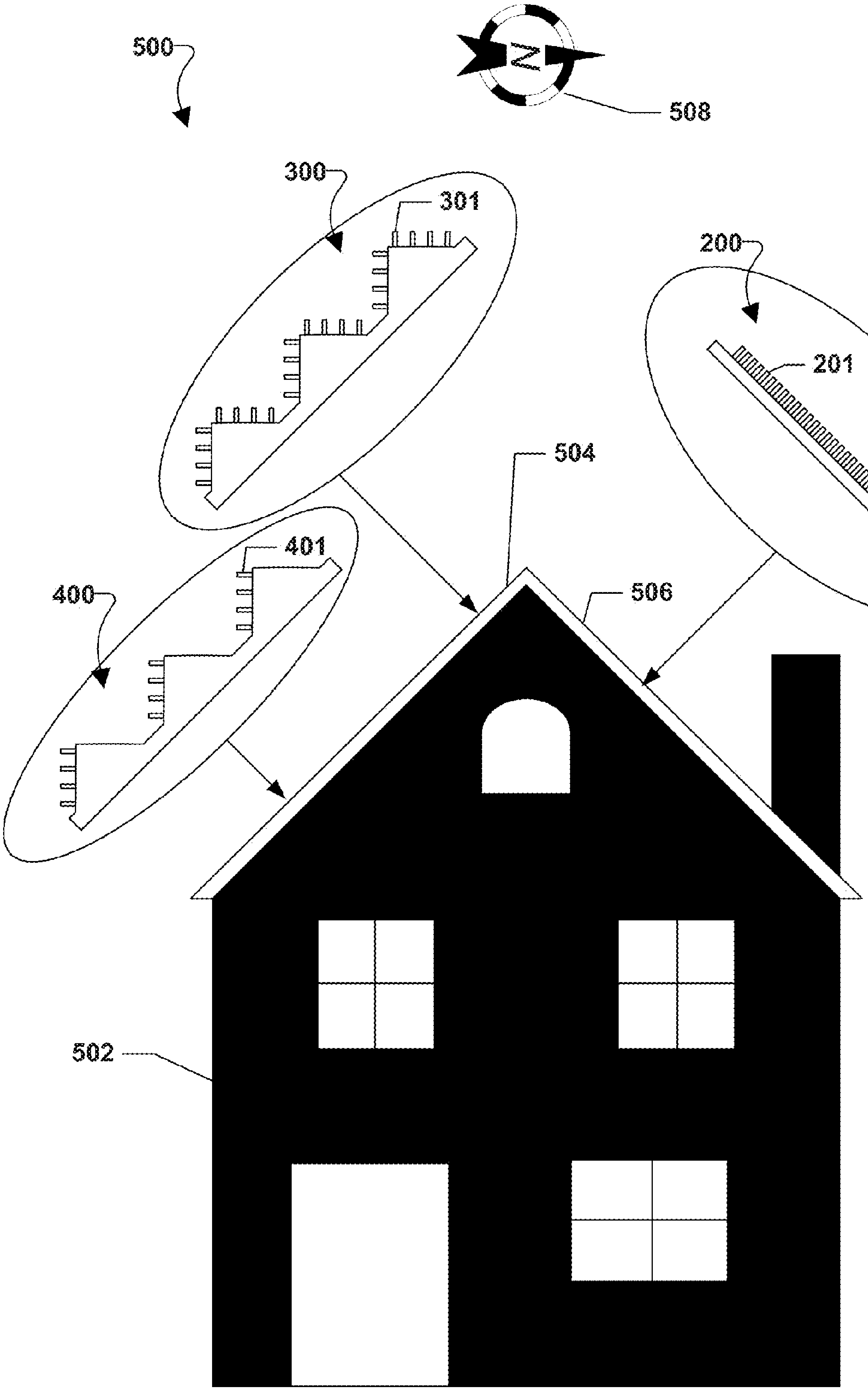

FIG. 5

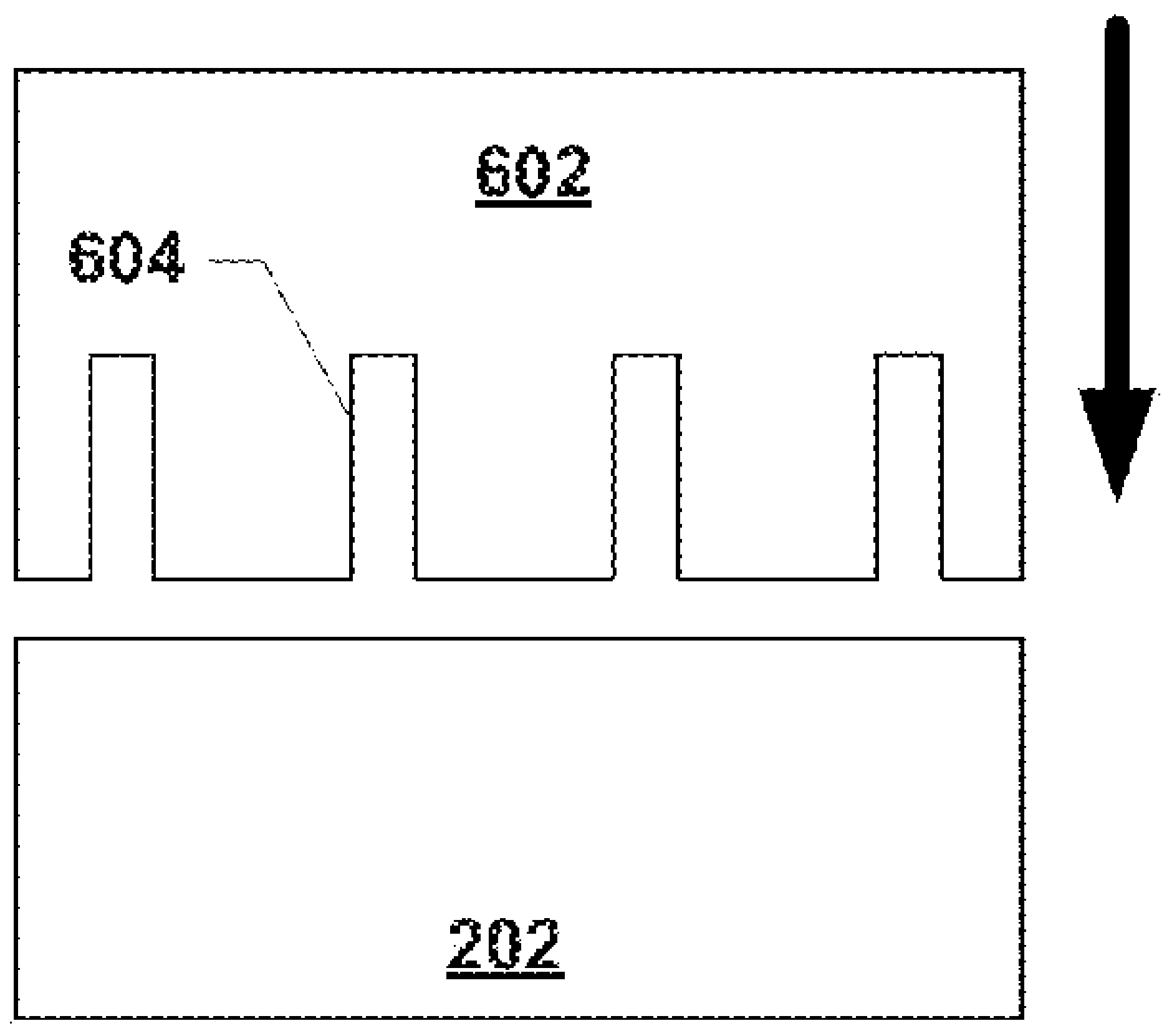

FIG. 6A

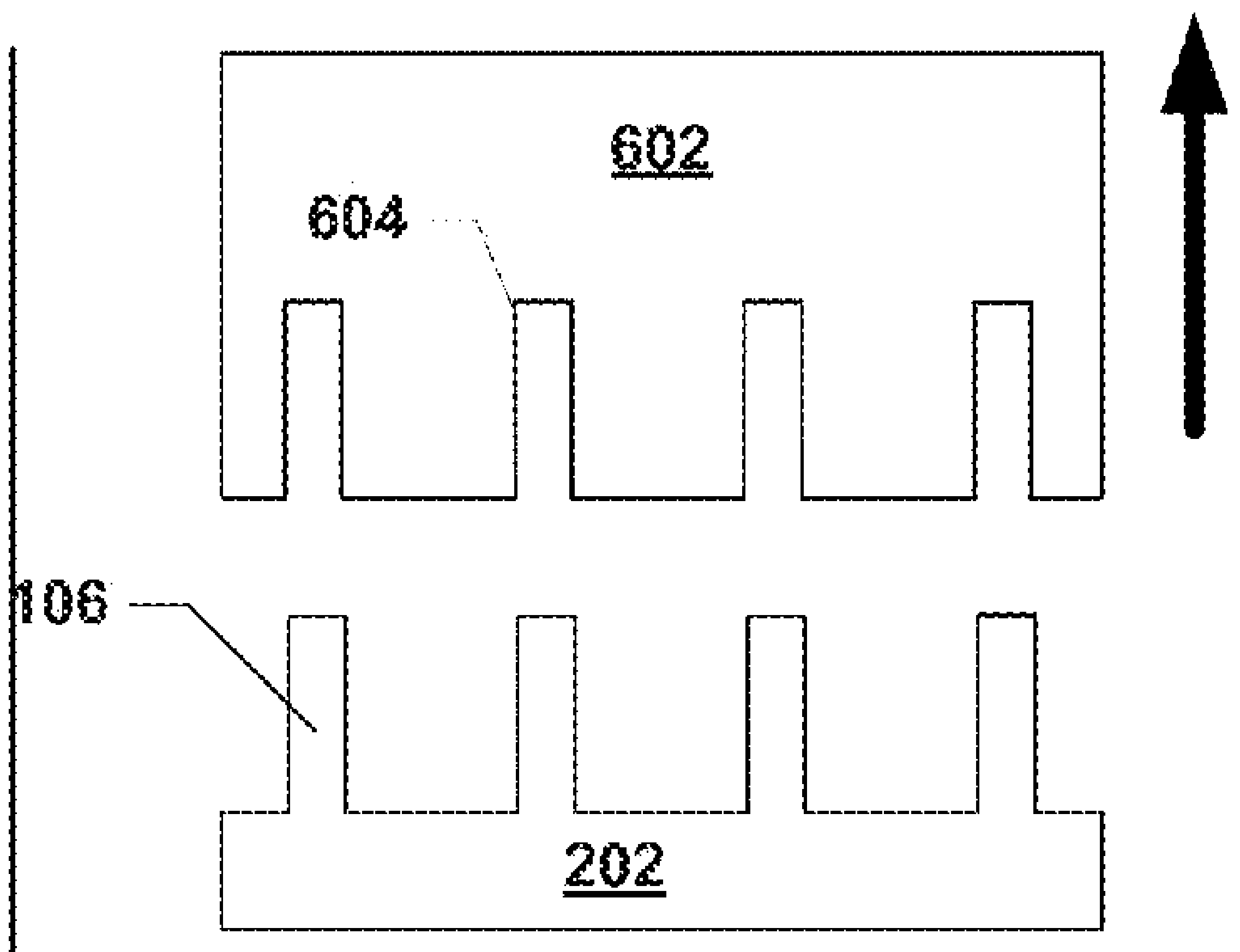

FIG. 6B

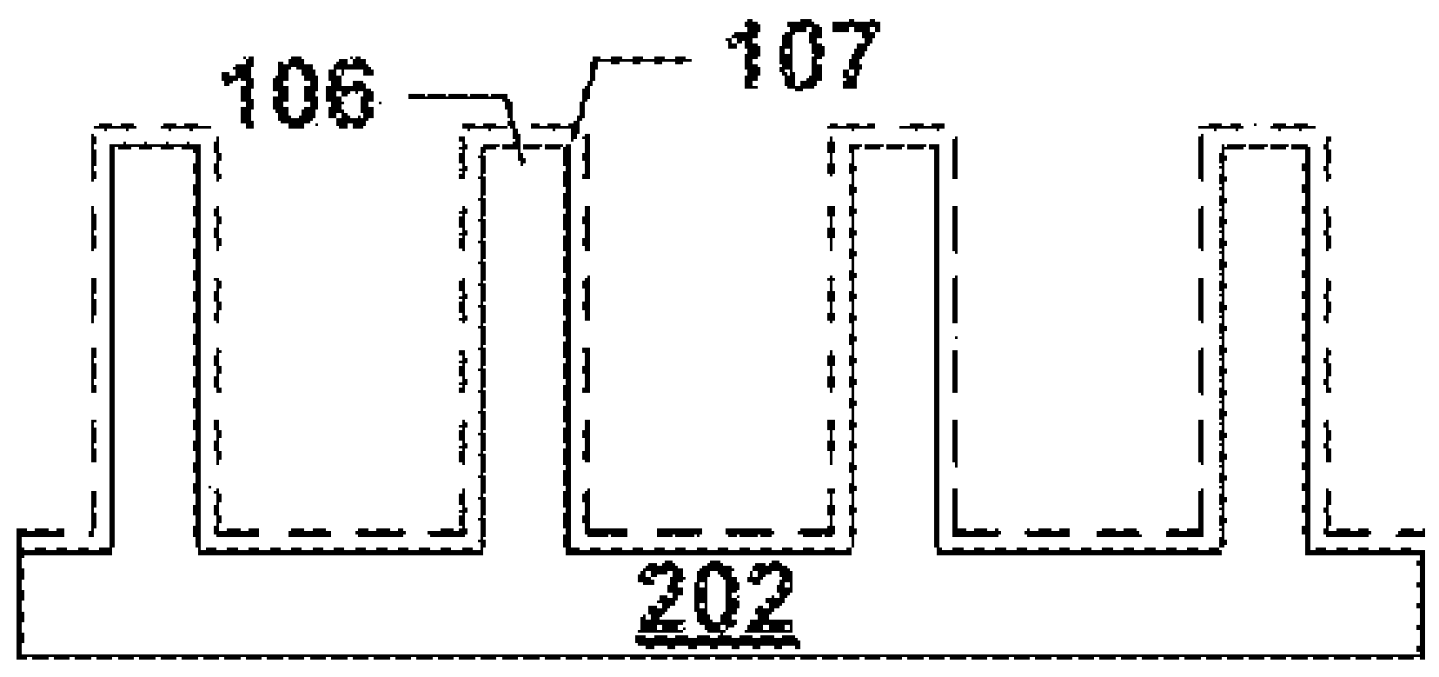

FIG. 6C

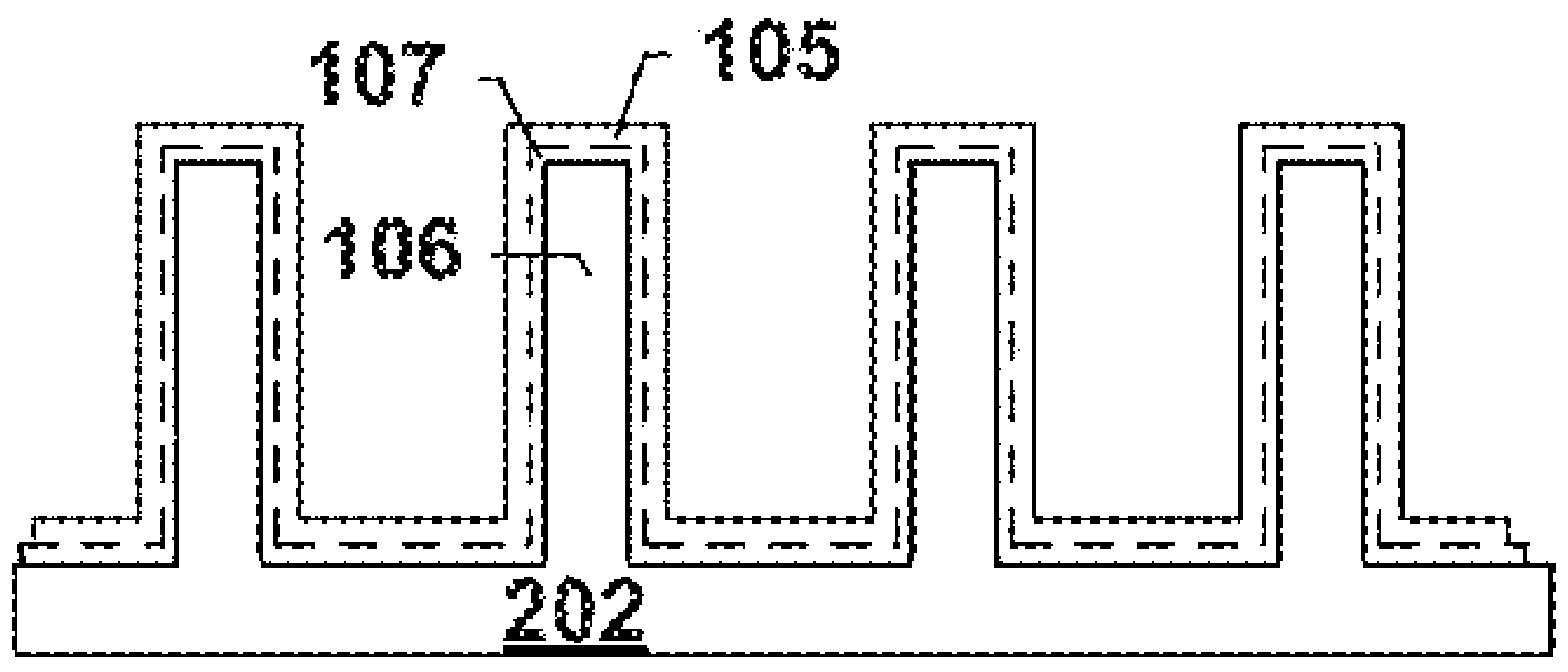

FIG. 6D

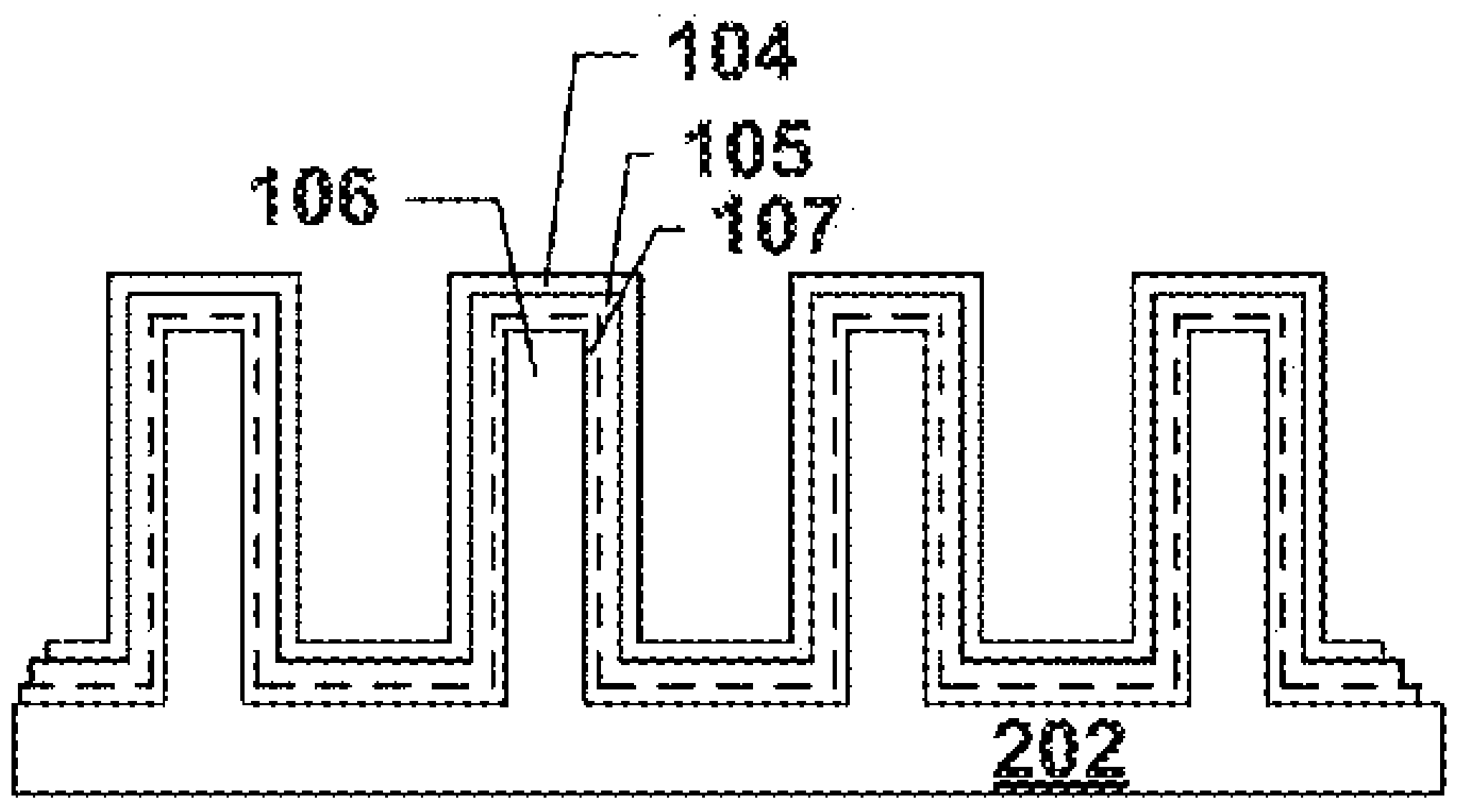

FIG. 6E

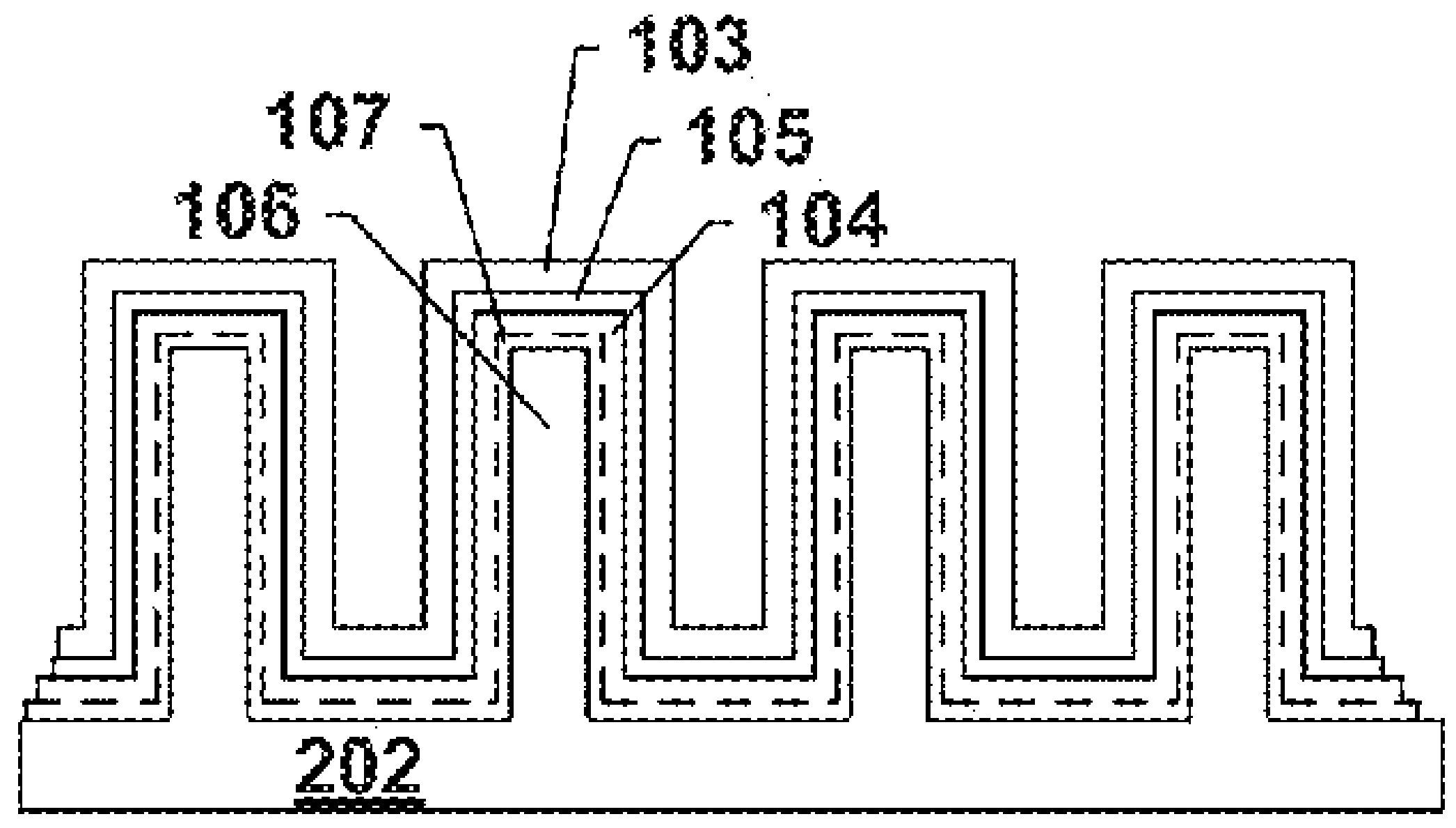

FIG. 6F

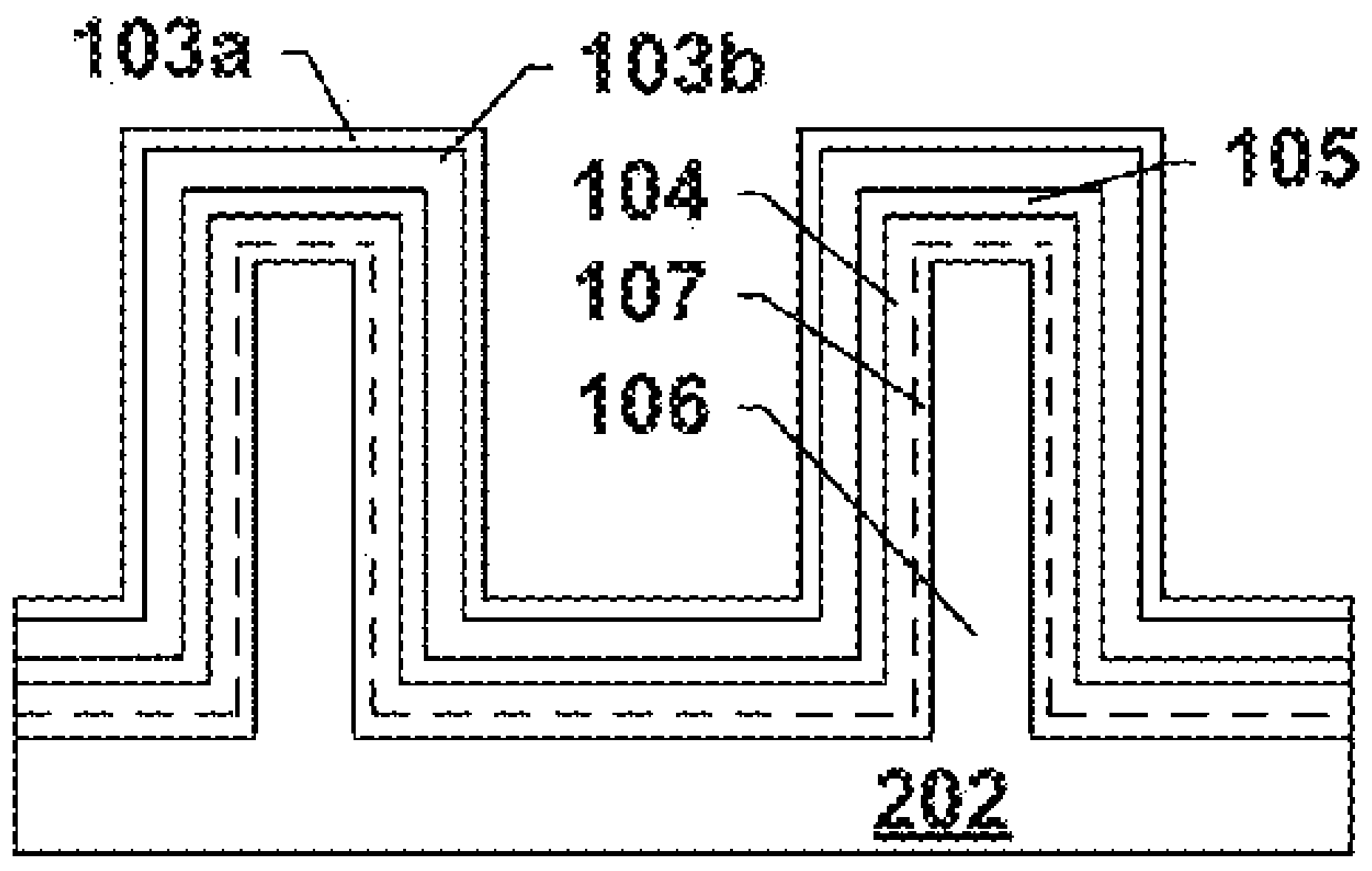

FIG. 6G

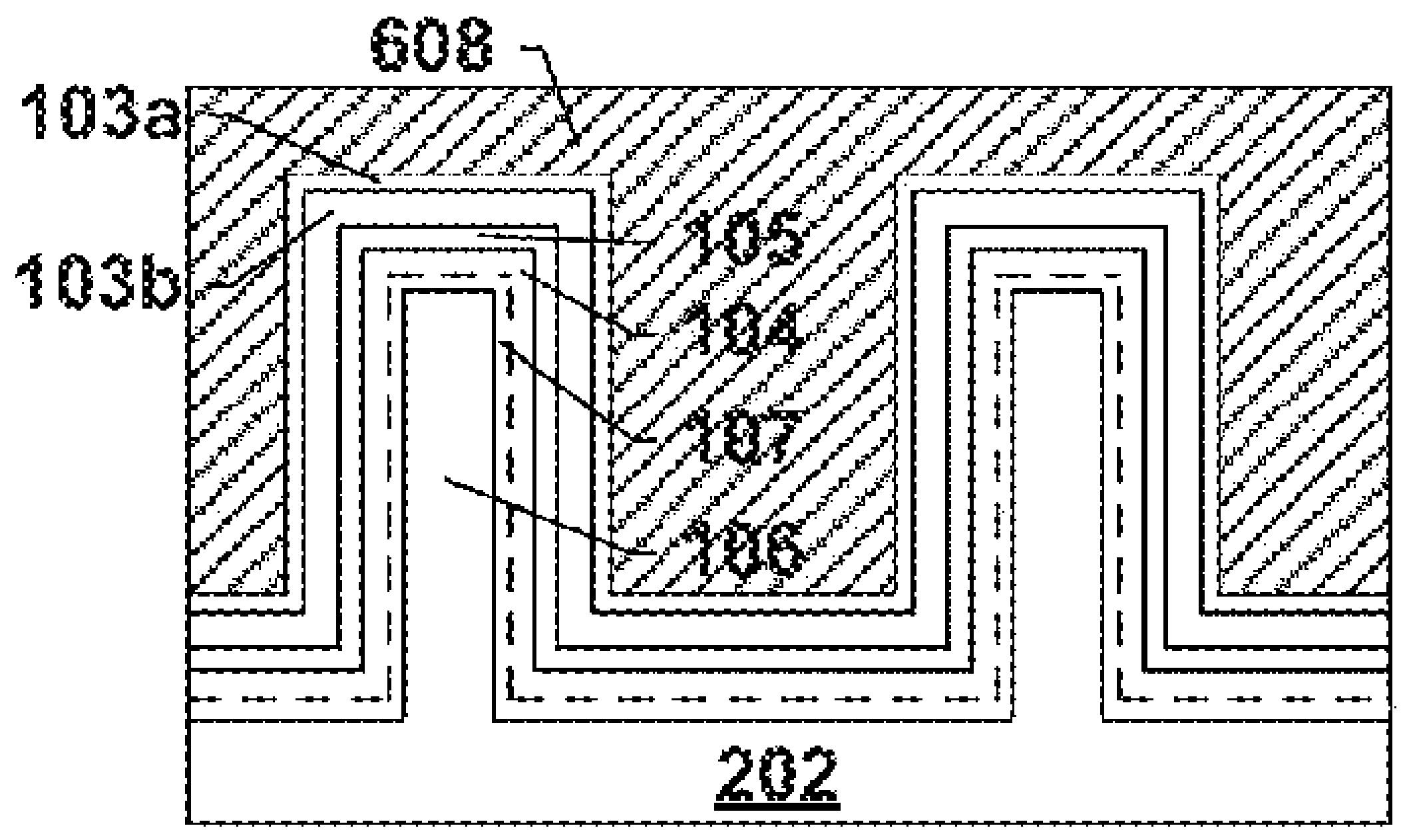

FIG. 6H

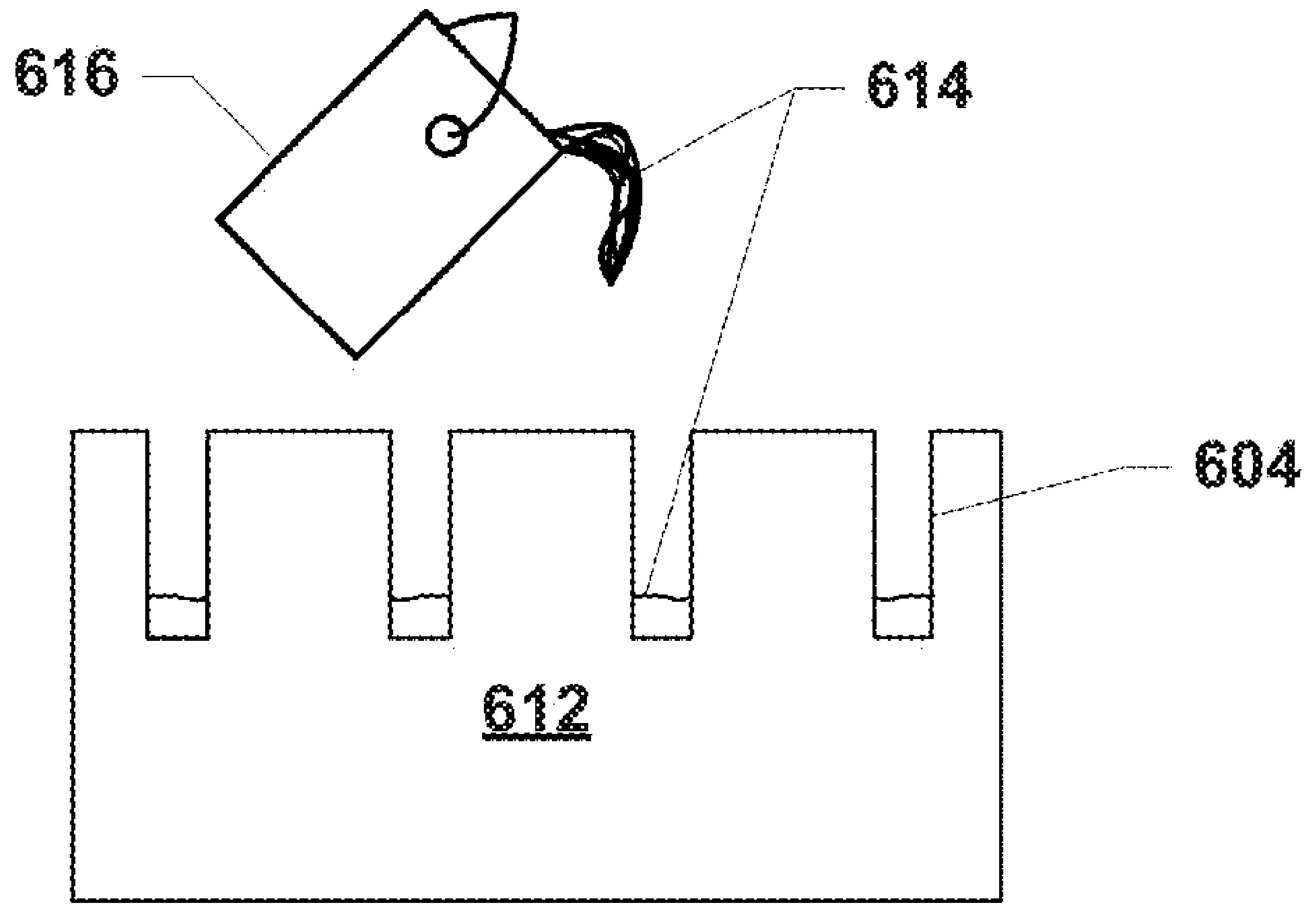

FIG. 6I

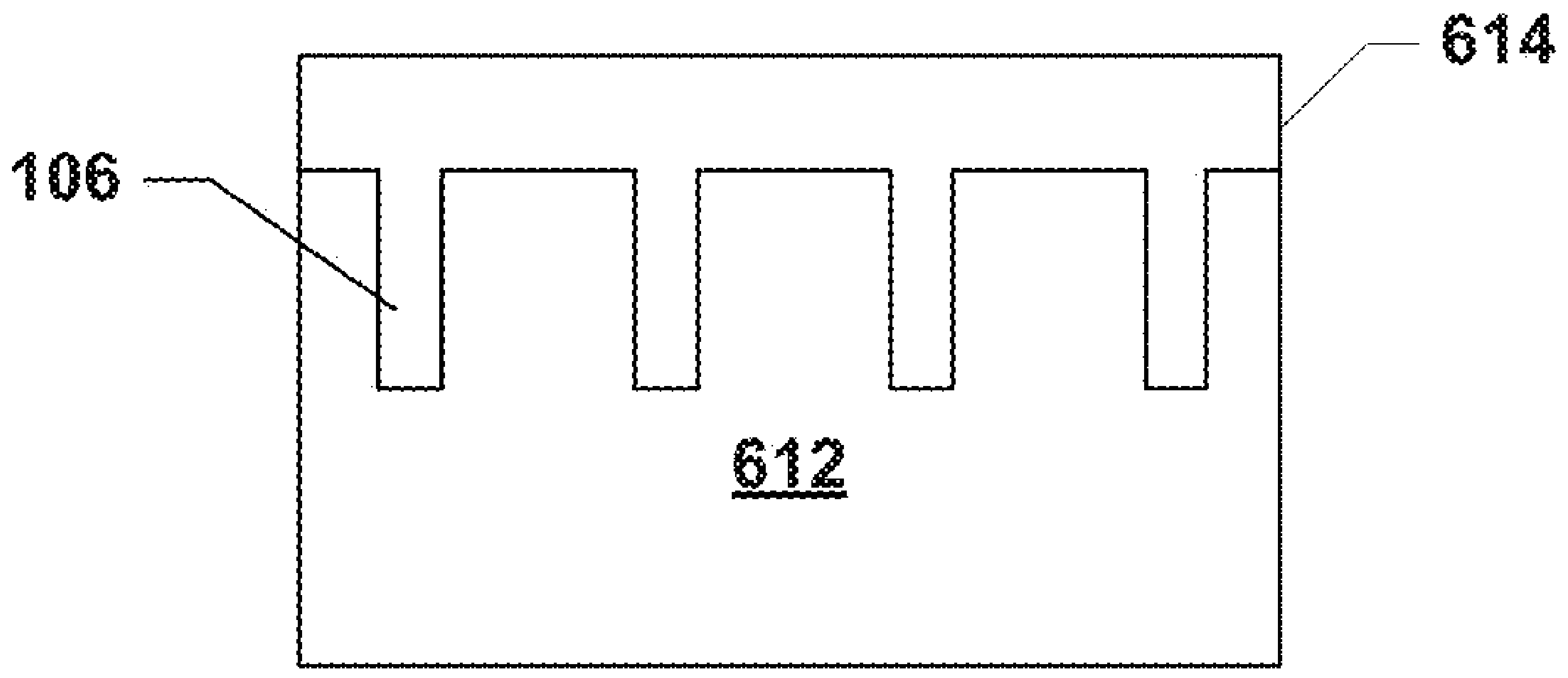

FIG. 6J

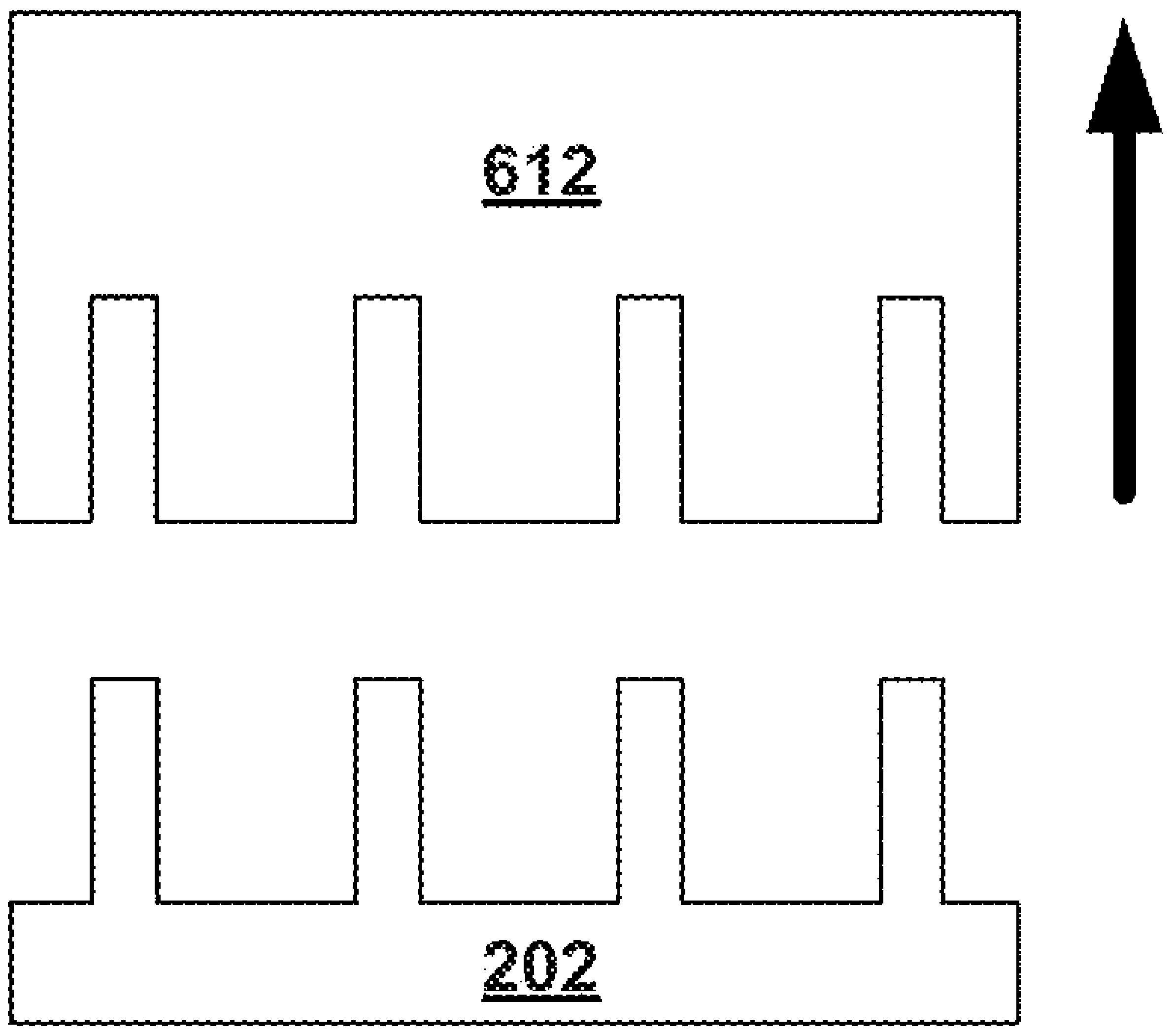

FIG. 6K

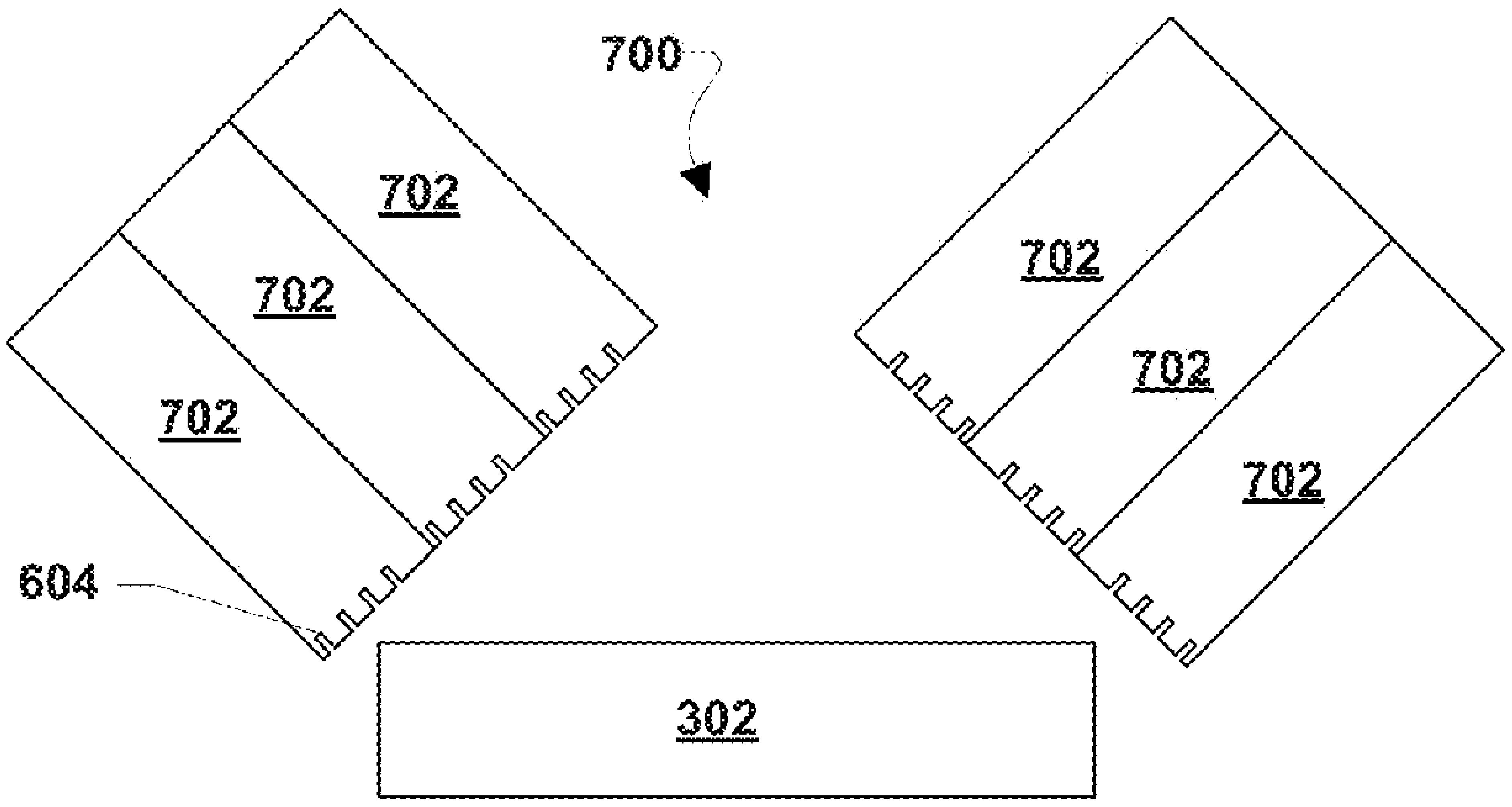

FIG. 7A

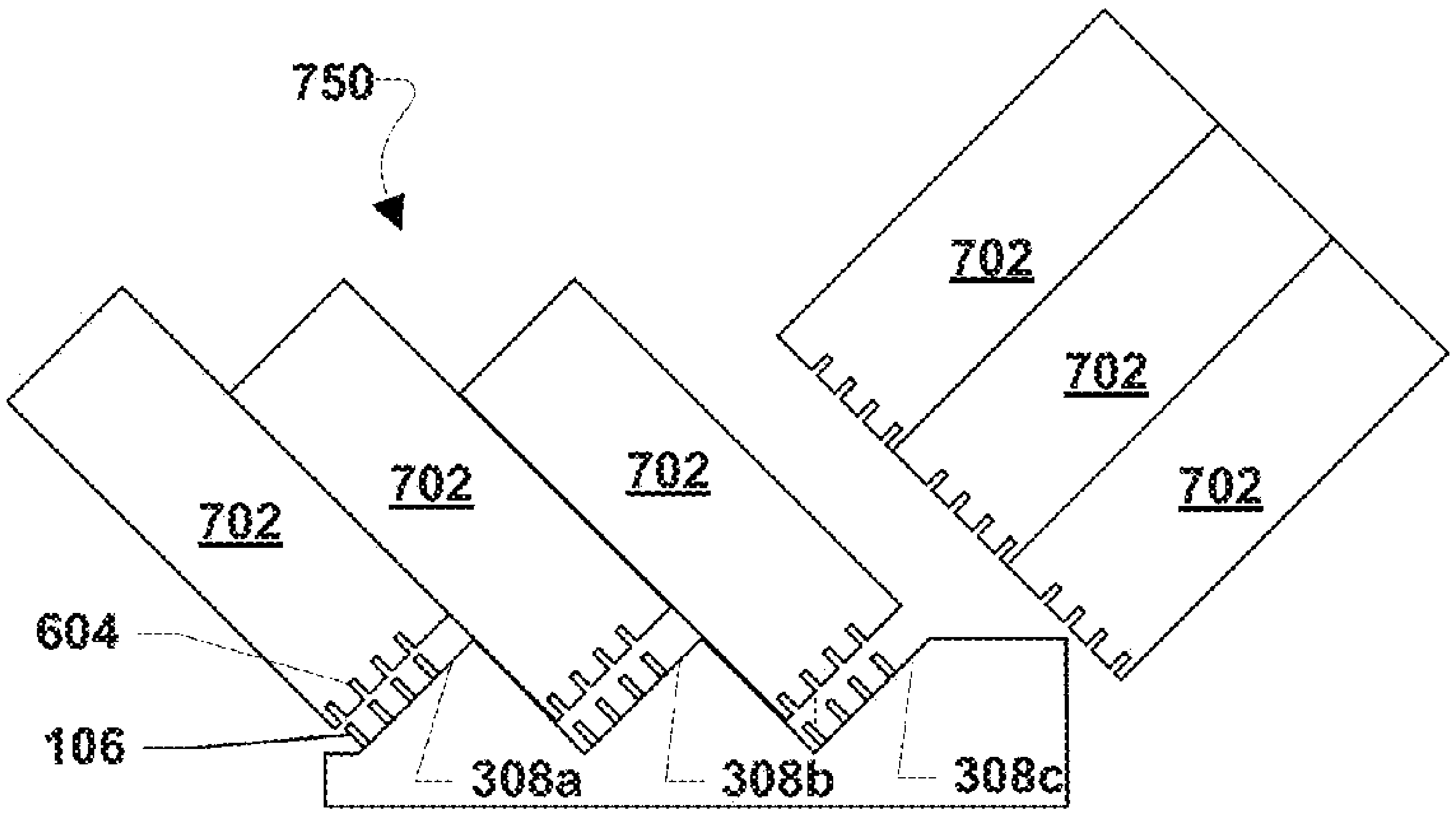

FIG. 7B

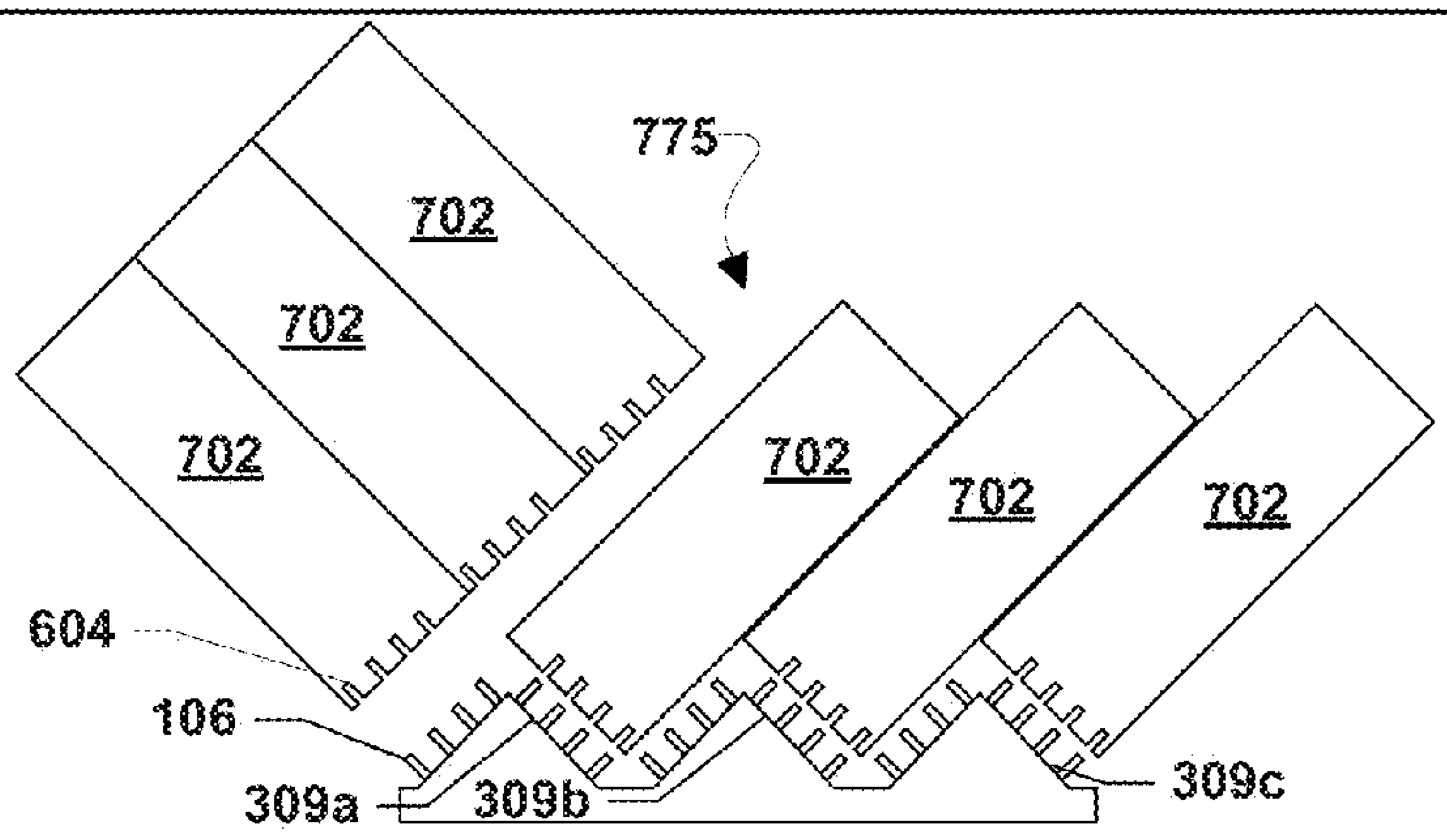

FIG. 7C

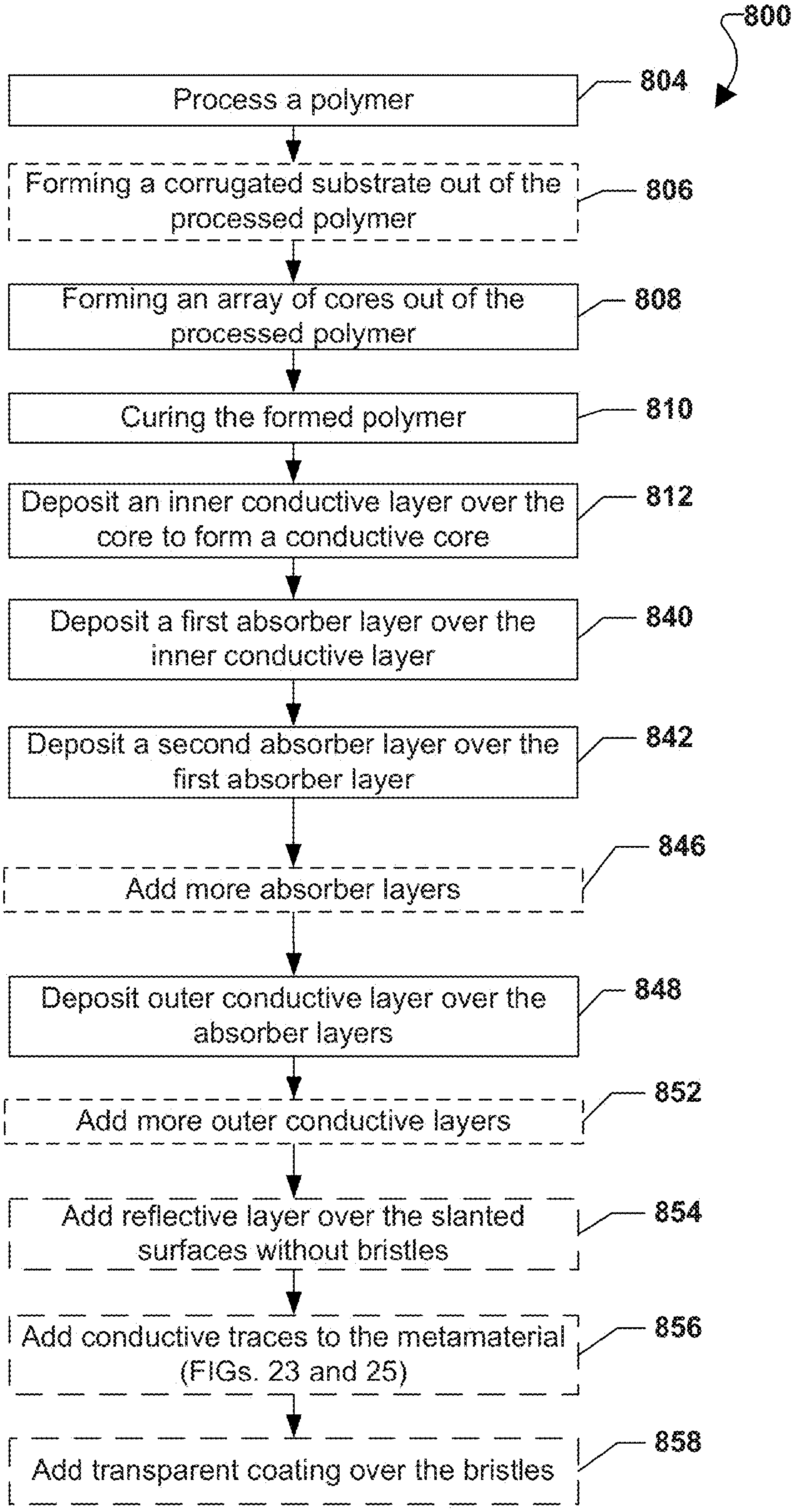
800
Process a polymer
804
Forming a corrugated substrate out of the processed polymer
806
Forming an array of cores out of the processed polymer
808
Curing the formed polymer
810
Deposit an inner conductive layer over the core to form a conductive core
812
Deposit a first absorber layer over the inner conductive layer
840
Deposit a second absorber layer over the first absorber layer
842
Add more absorber layers
846
Deposit outer conductive layer over the absorber layers
848
Add more outer conductive layers
852
Add reflective layer over the slanted surfaces without bristles
854
Add conductive traces to the metamaterial (FIGs. 23 and 25)
856
Add transparent coating over the bristles
858

FIG. 8

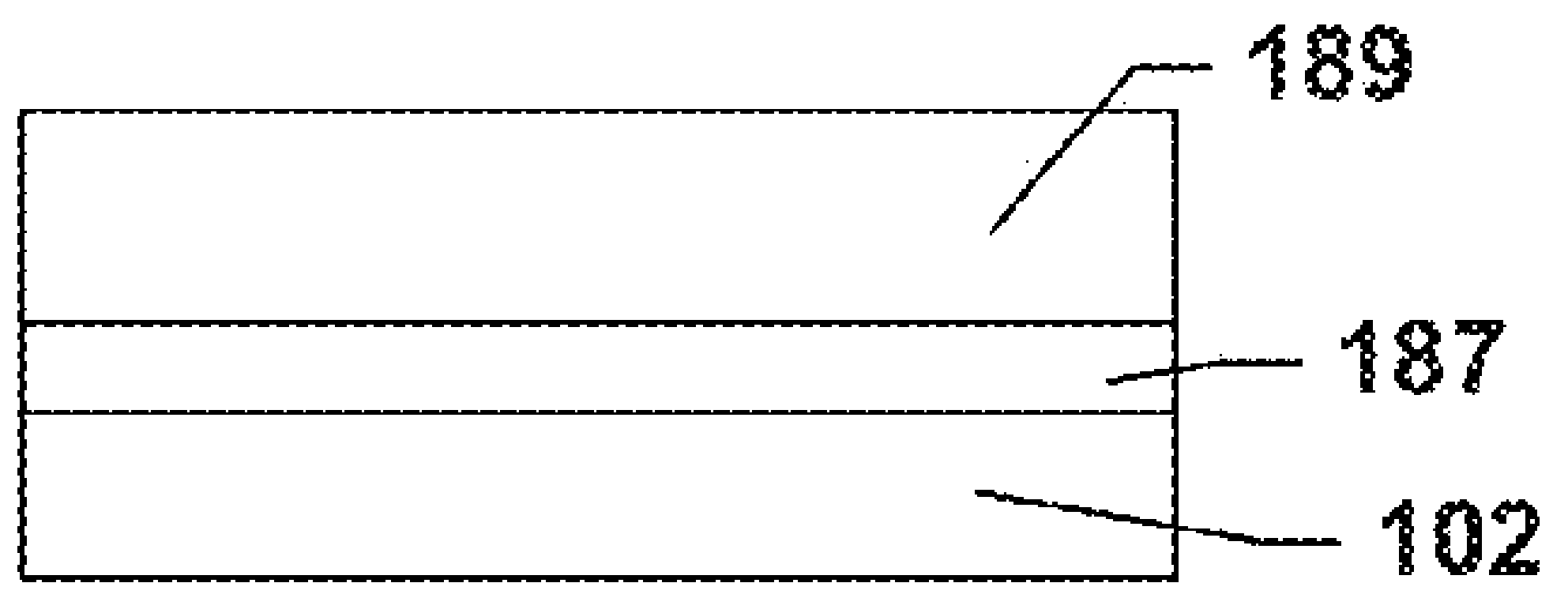

FIG. 9A

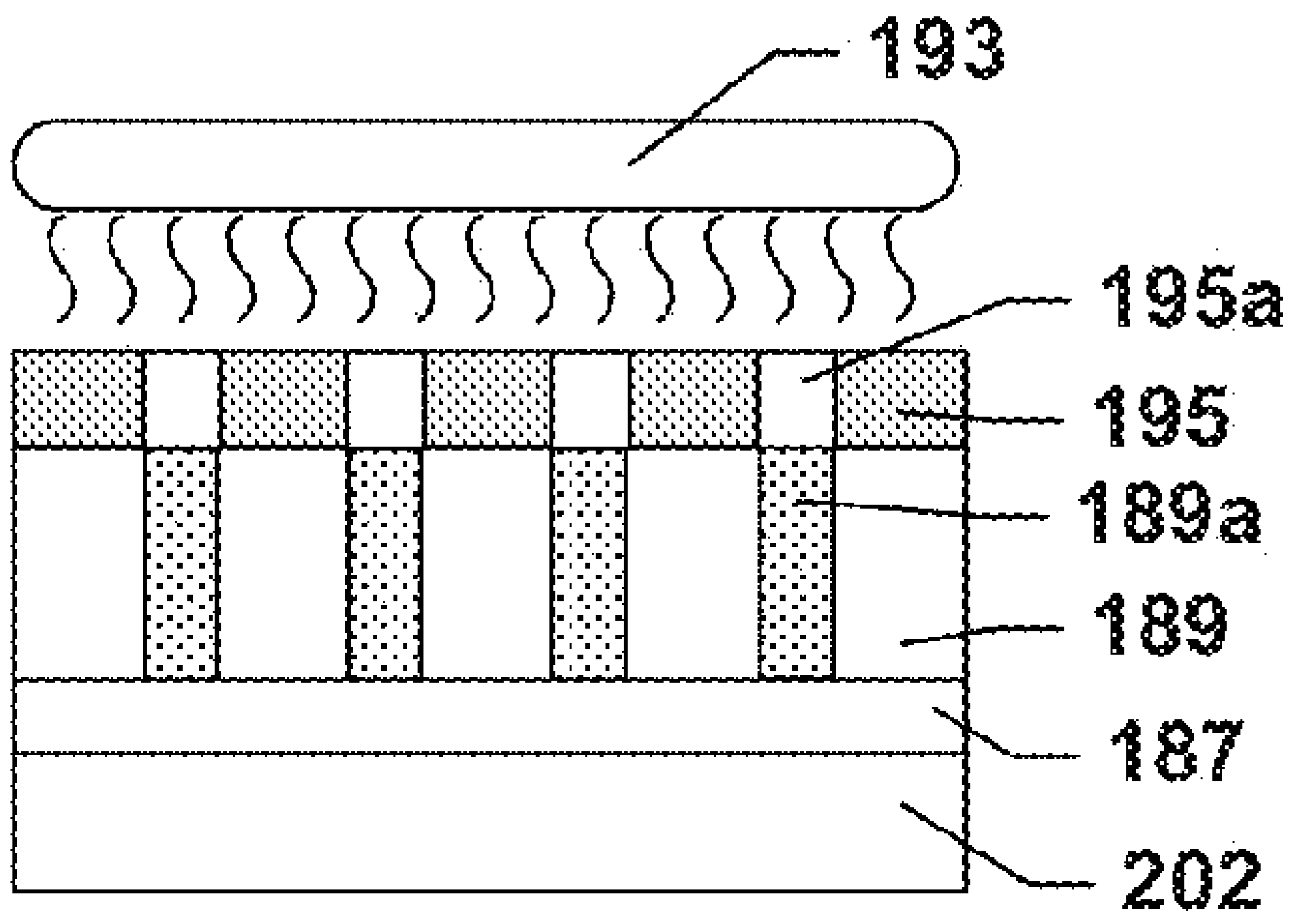

FIG. 9B

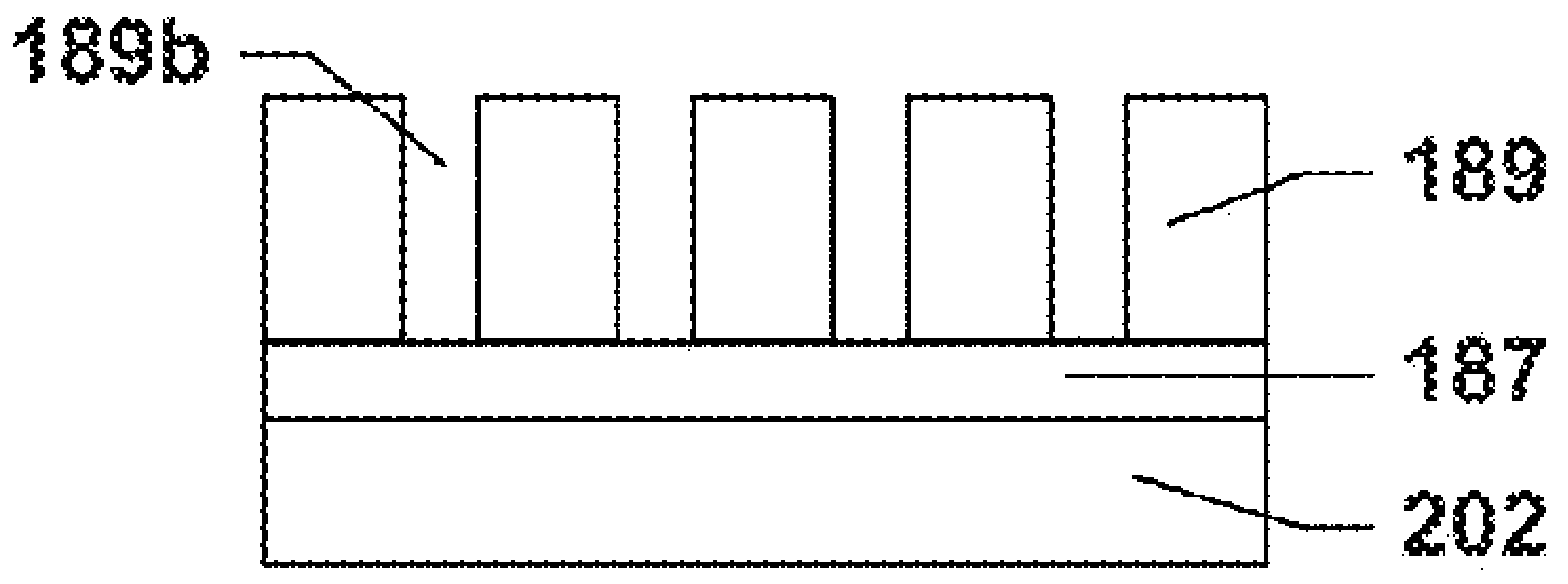

FIG. 9C

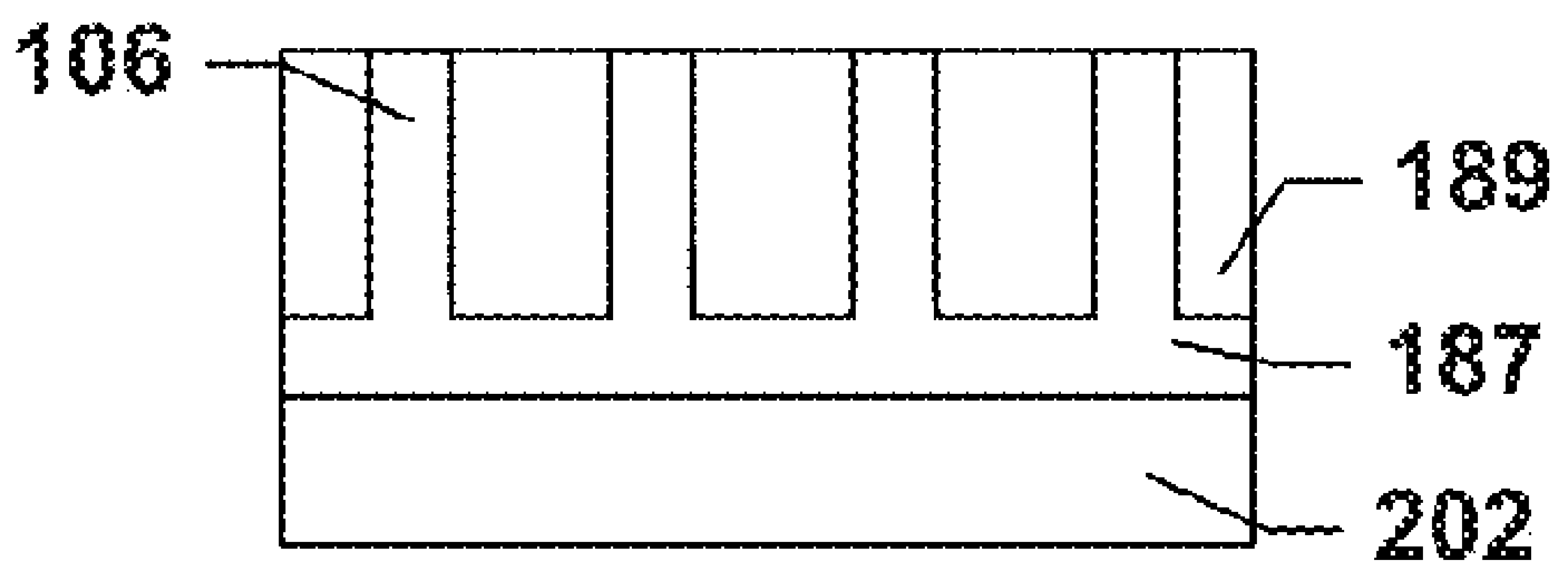

FIG. 9D

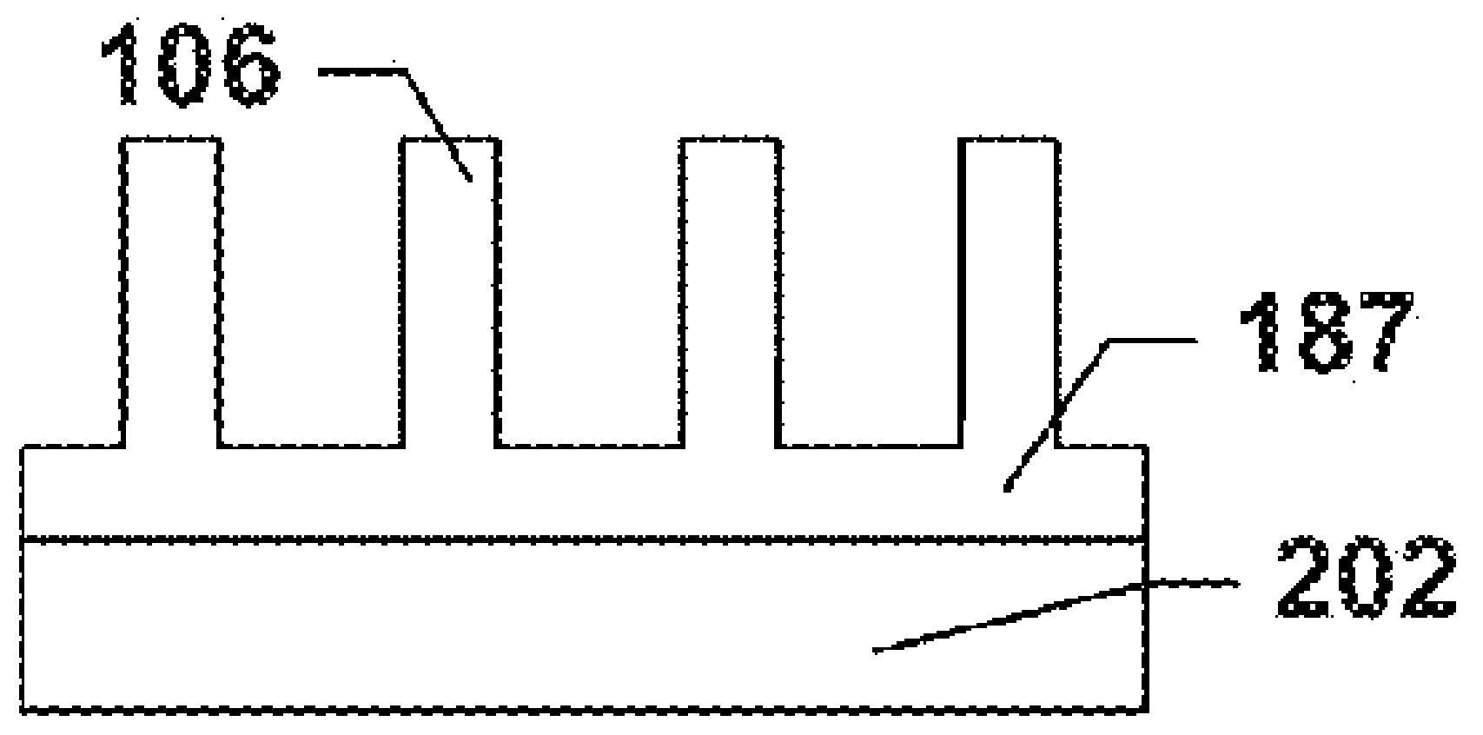

FIG. 9E

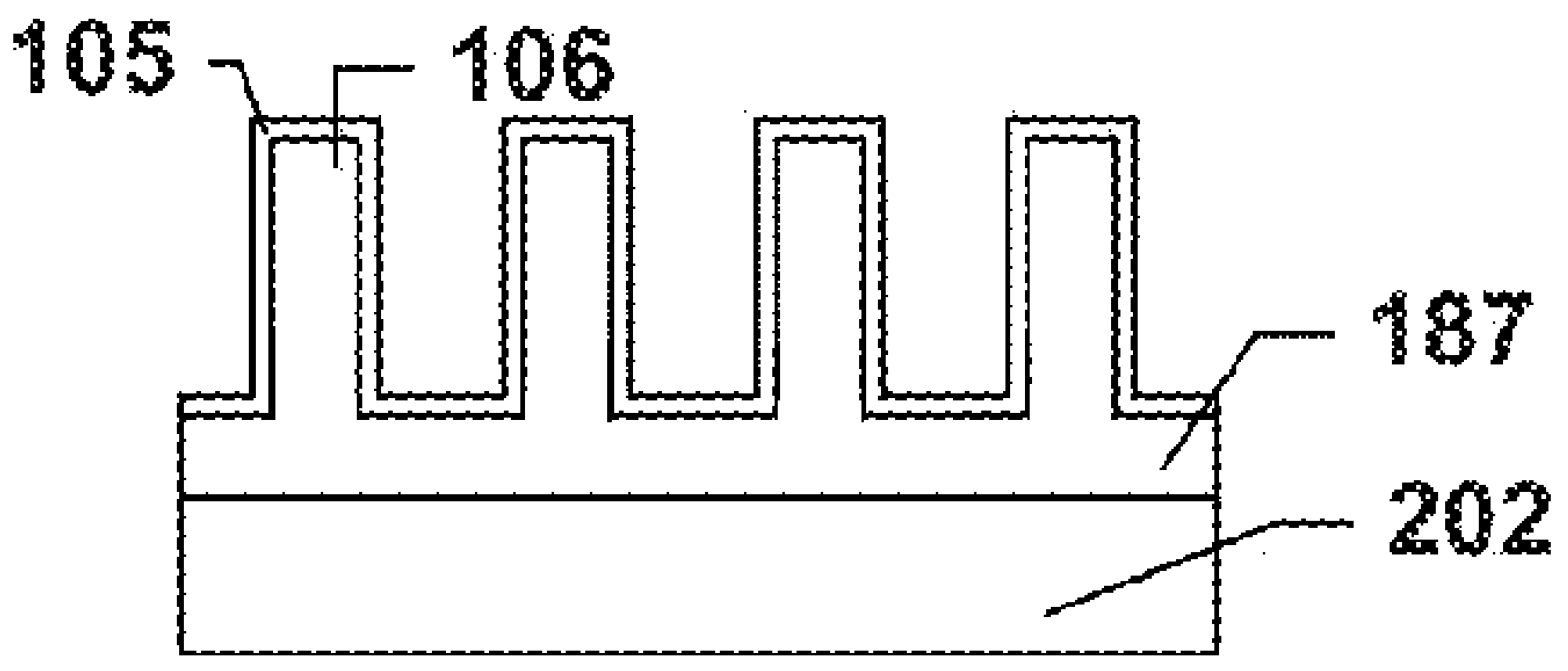

FIG. 9F

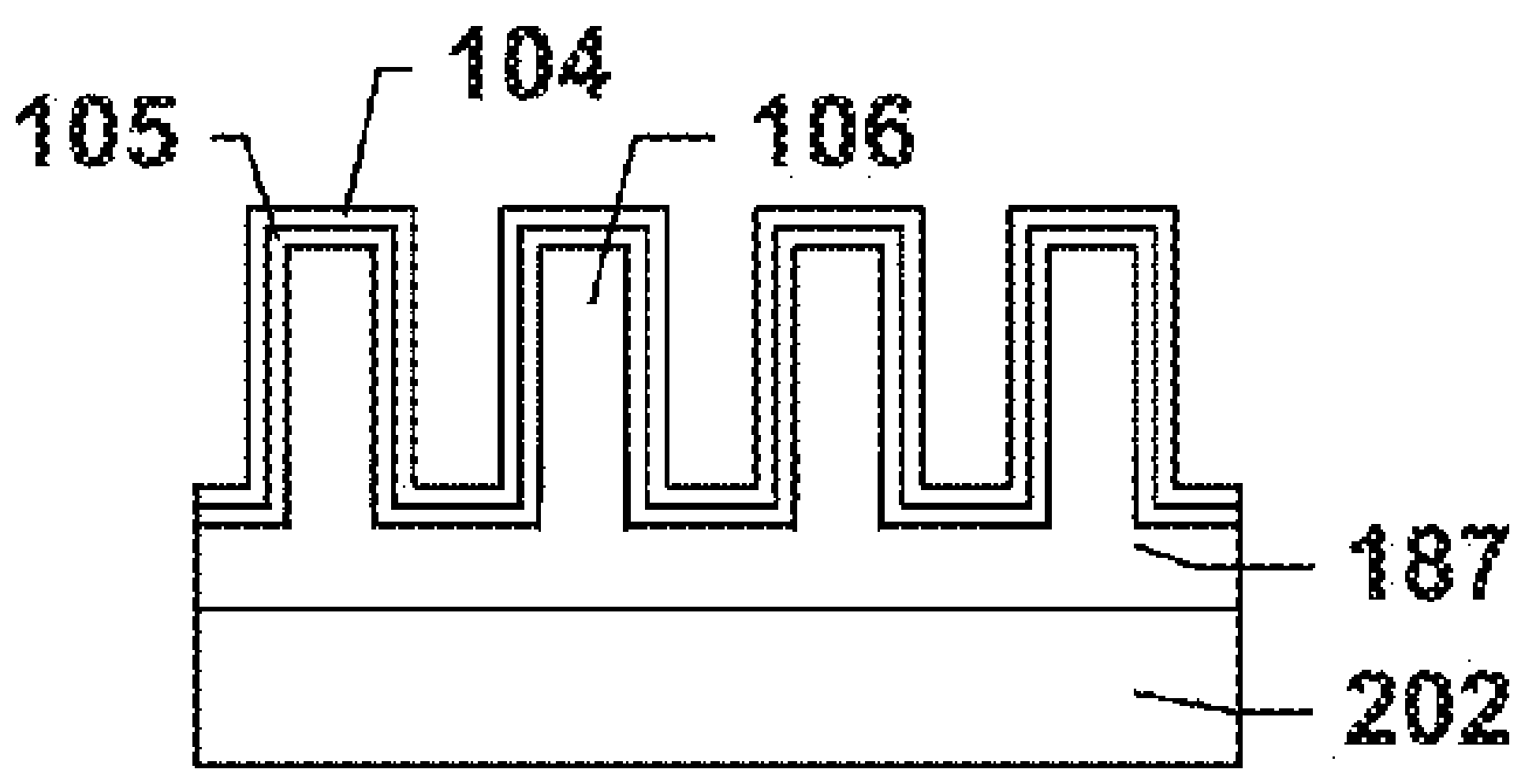

FIG. 9G

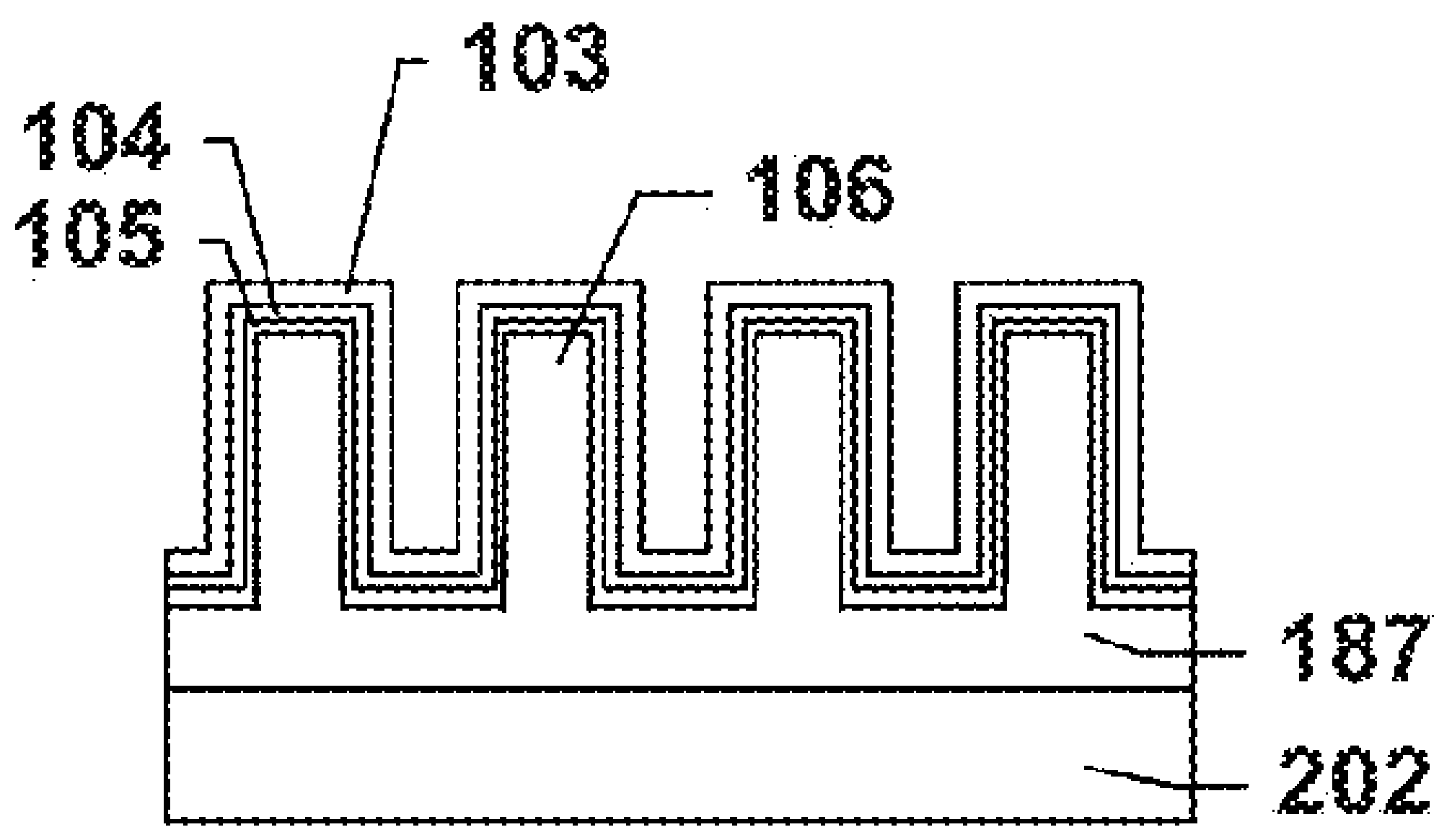

FIG. 9H

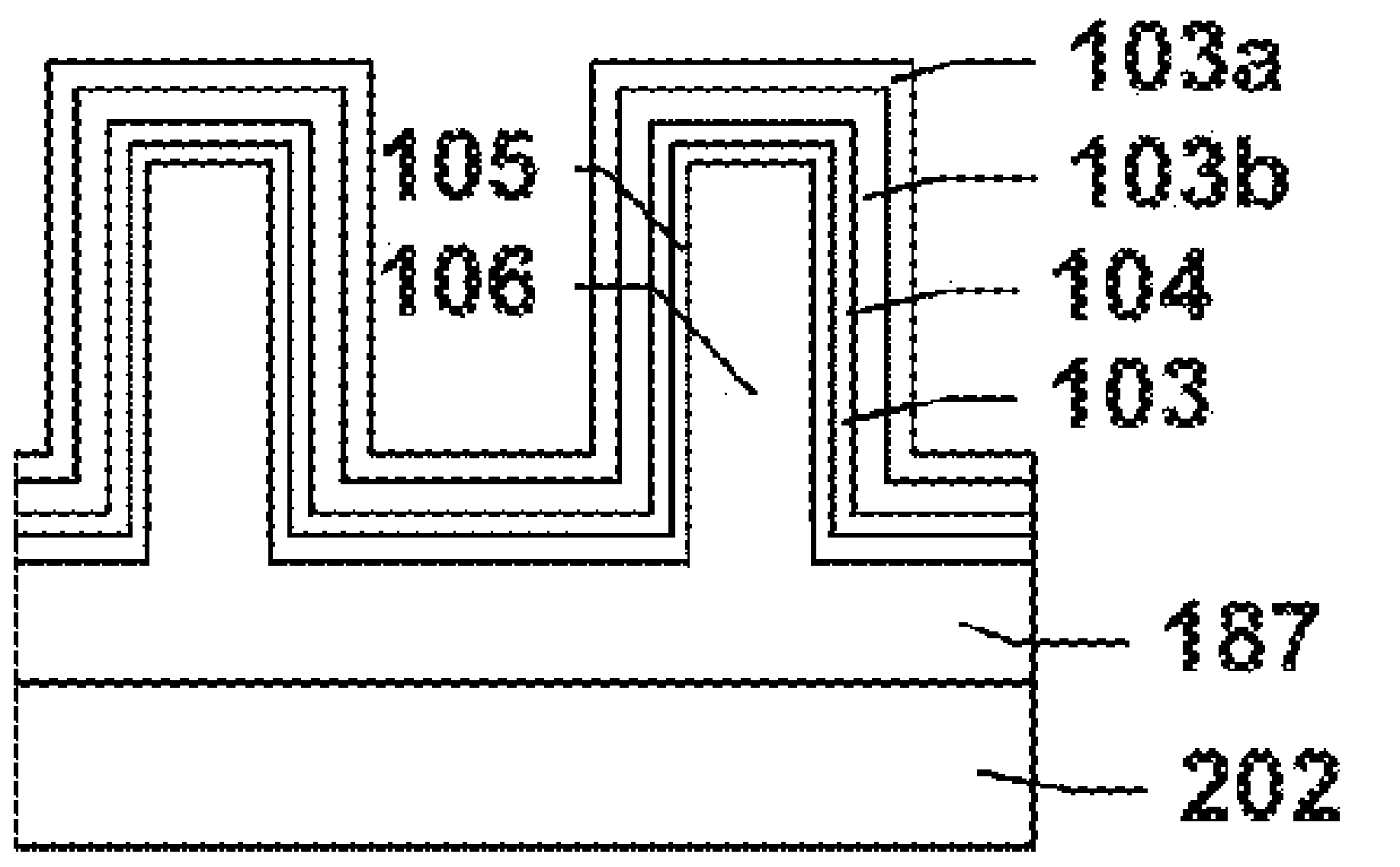

FIG. 9I

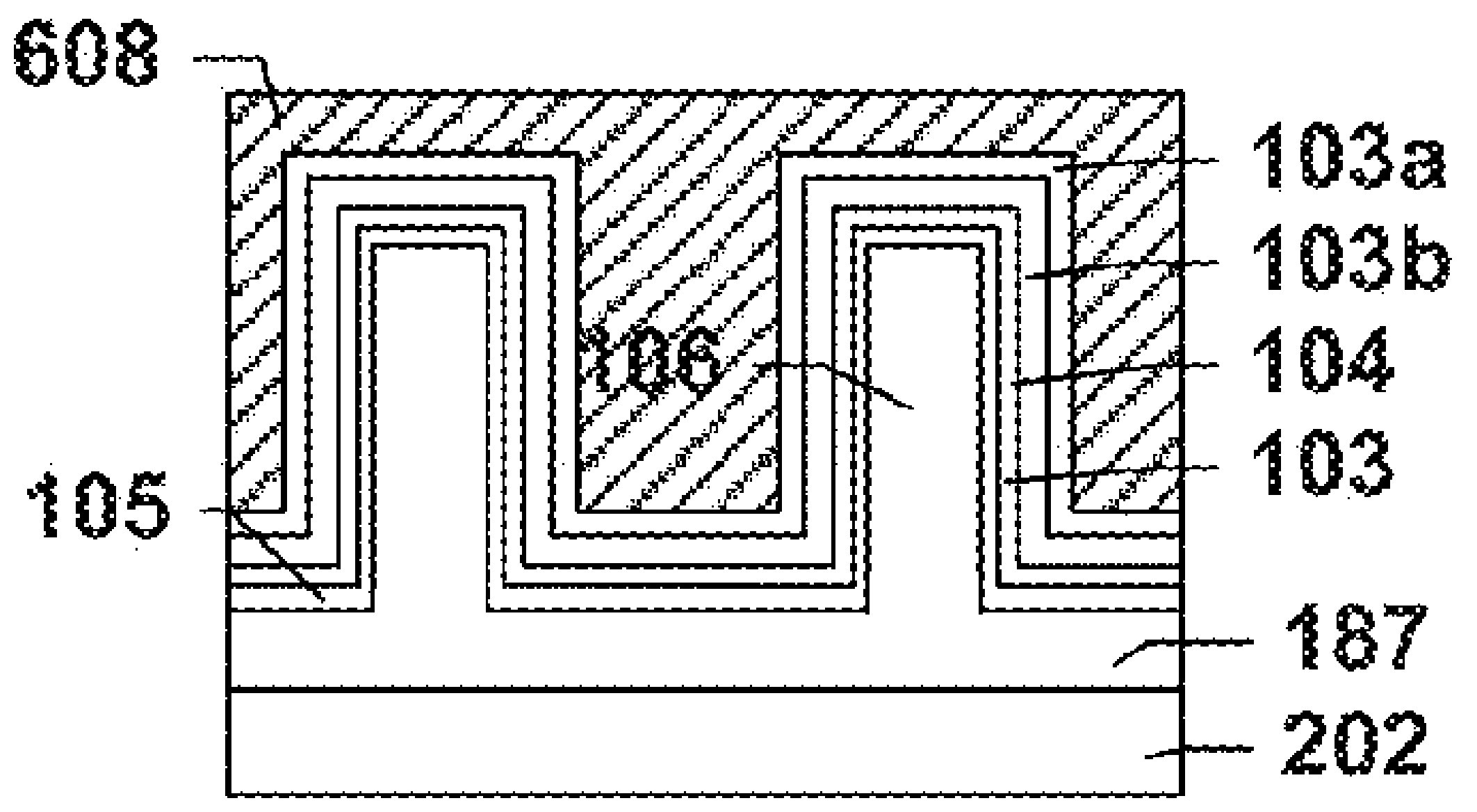

FIG. 9J

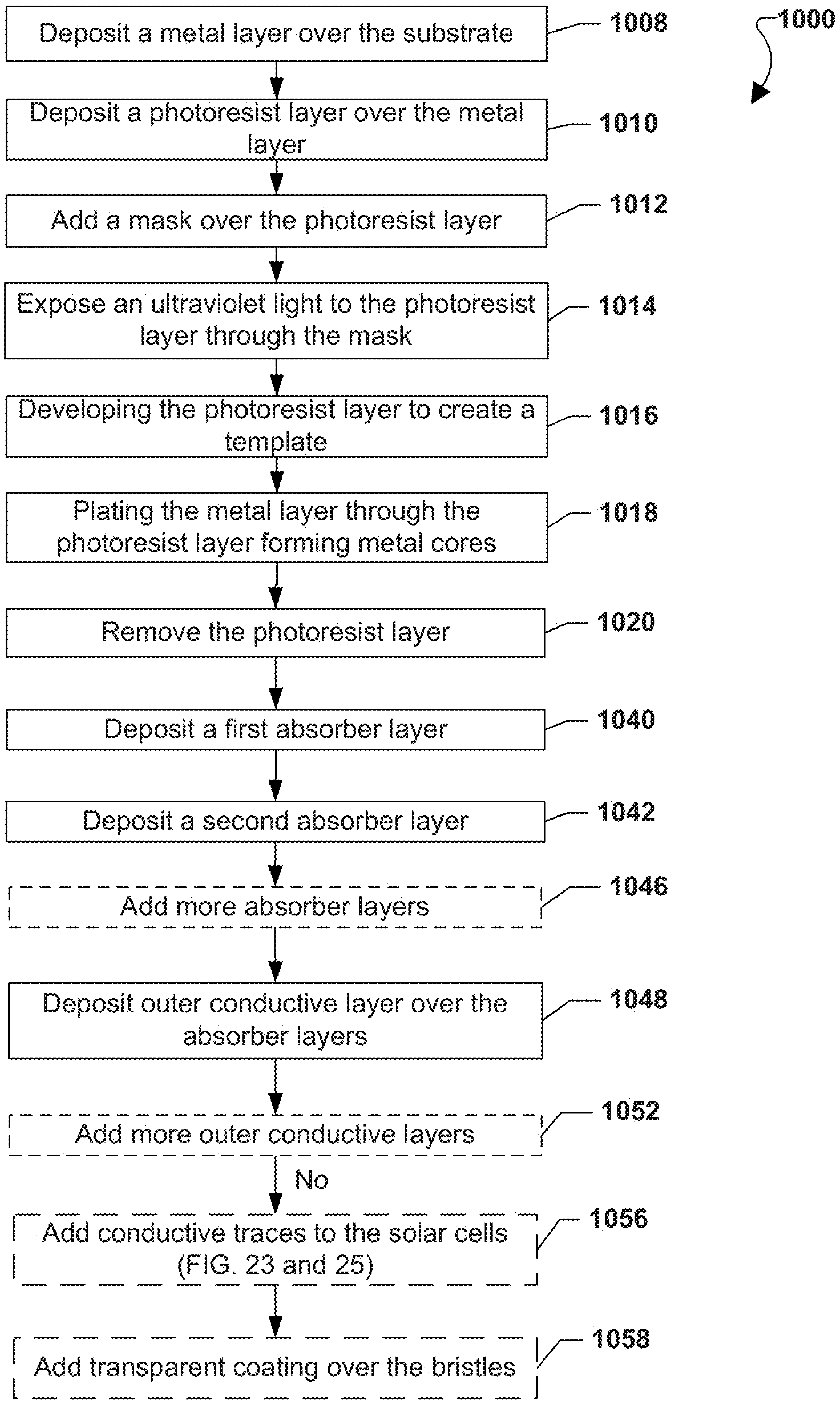
1000
Deposit a metal layer over the substrate
1008
Deposit a photoresist layer over the metal layer
1010
Add a mask over the photoresist layer
1012
Expose an ultraviolet light to the photoresist layer through the mask
1014
Developing the photoresist layer to create a template
1016
Plating the metal layer through the photoresist layer forming metal cores
1018
Remove the photoresist layer
1020
Deposit a first absorber layer
1040
Deposit a second absorber layer
1042
Add more absorber layers
1046
Deposit outer conductive layer over the absorber layers
1048
Add more outer conductive layers
1052
No
Add conductive traces to the solar cells (FIG. 23 and 25)
1056
Add transparent coating over the bristles
1058

FIG. 10

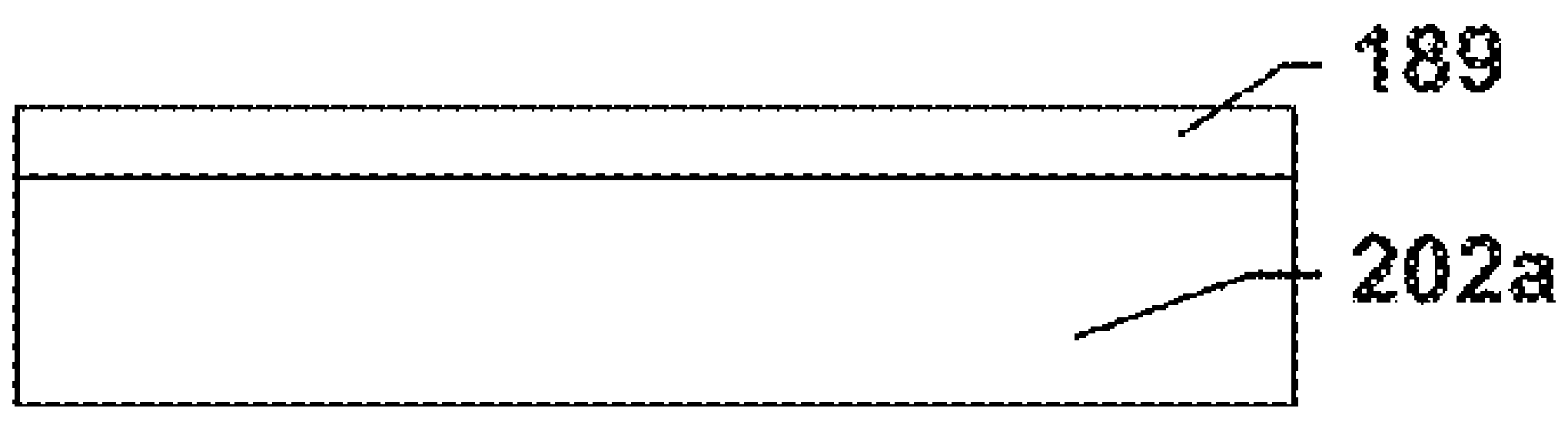

FIG. 11A

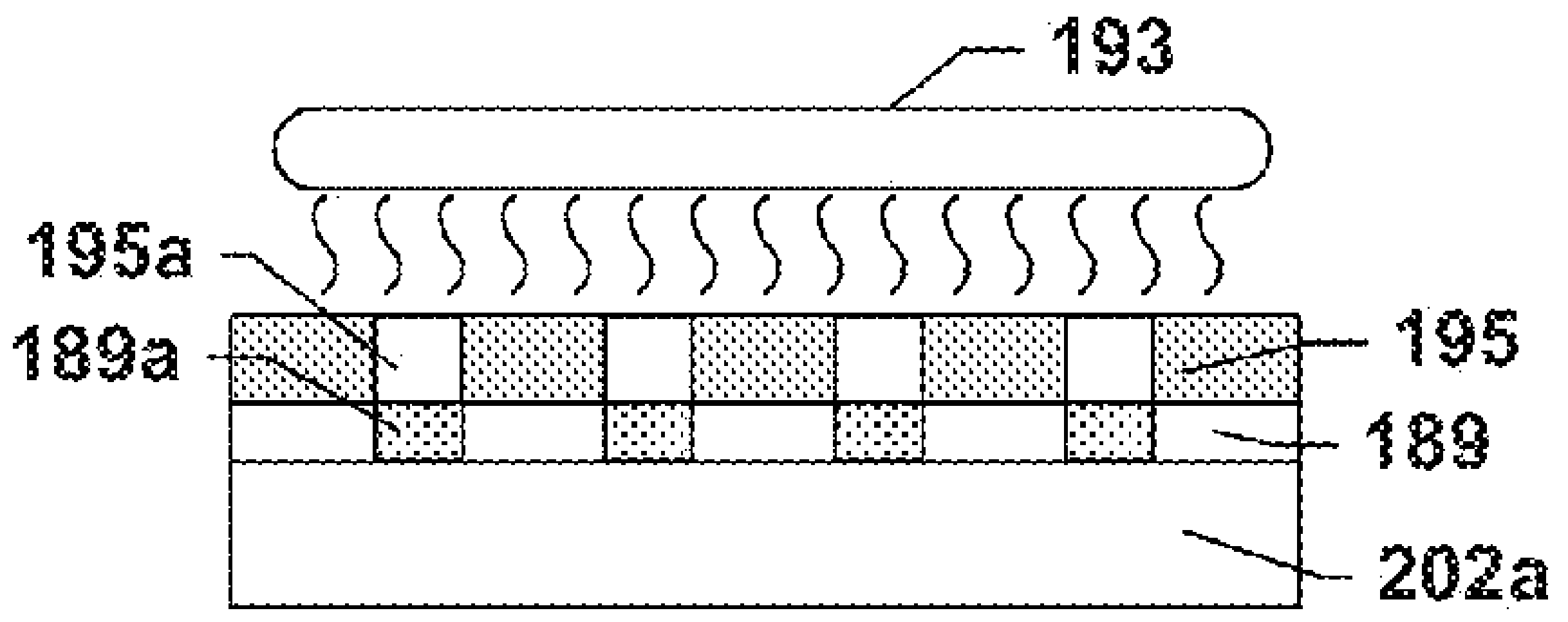

FIG. 11B

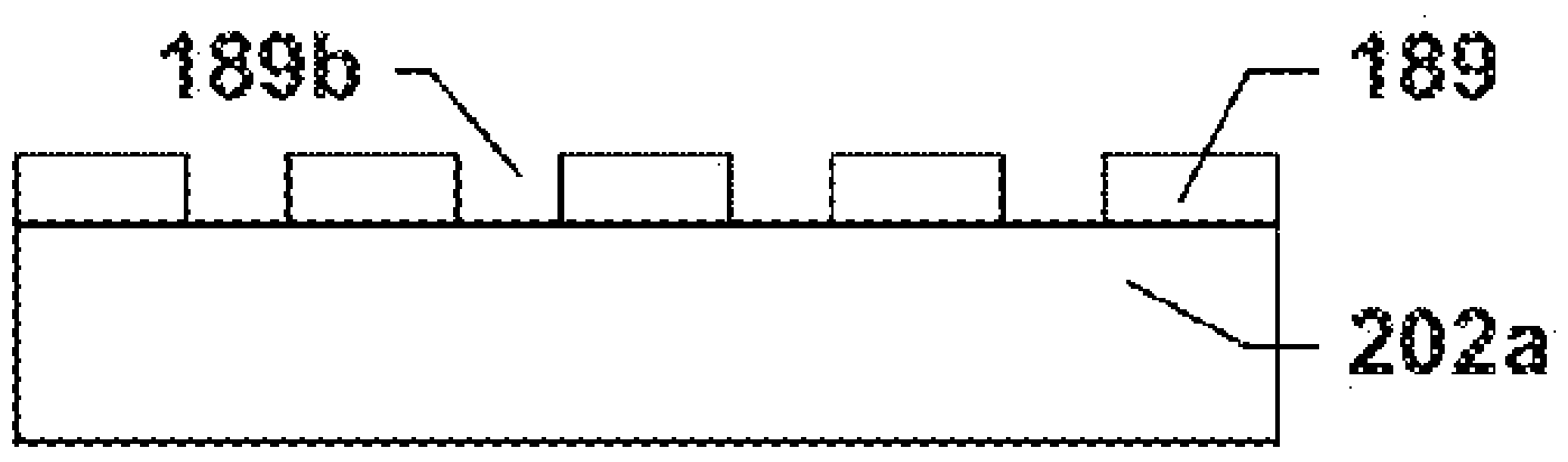

FIG. 11C

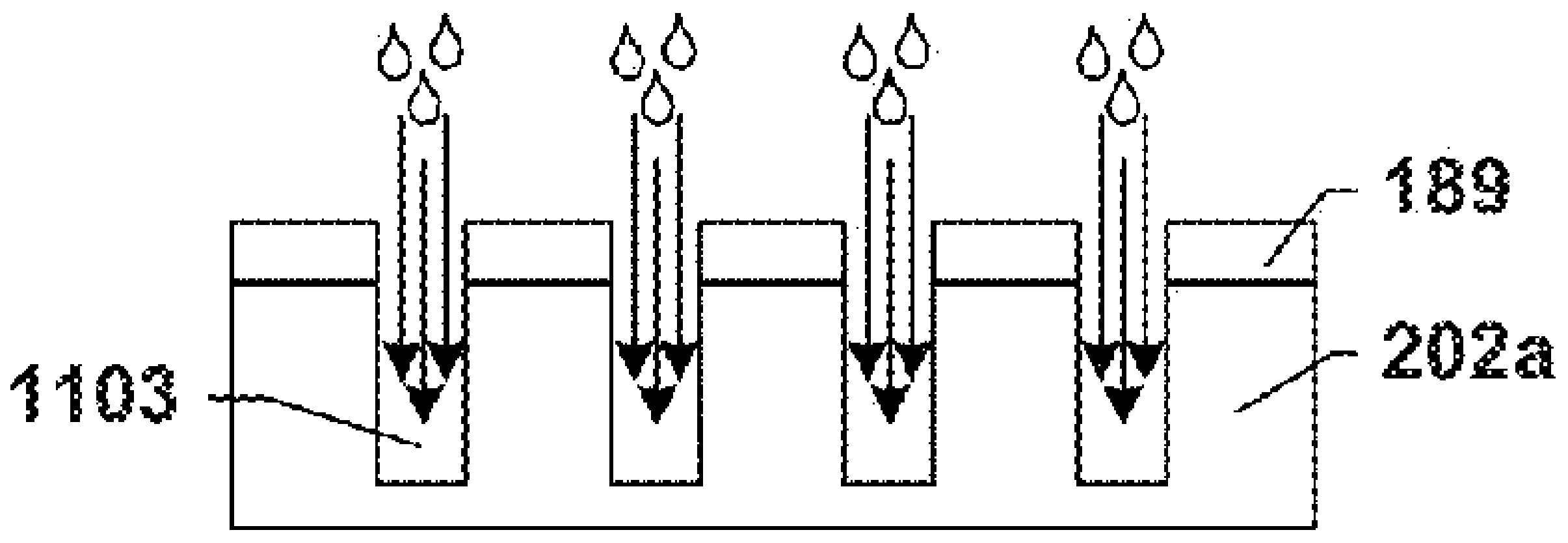

FIG. 11D

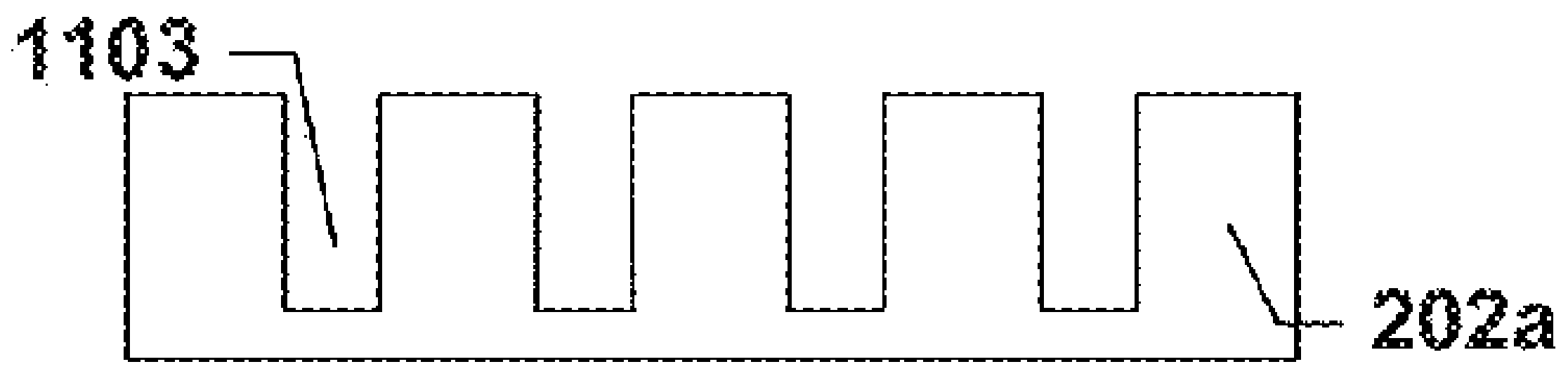

FIG. 11E

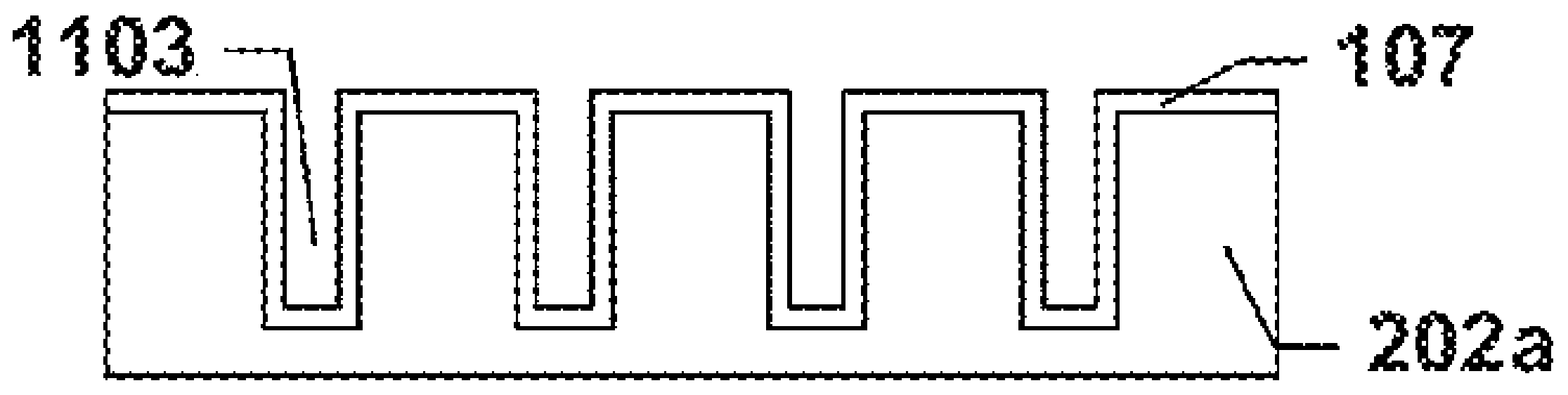

FIG. 11F

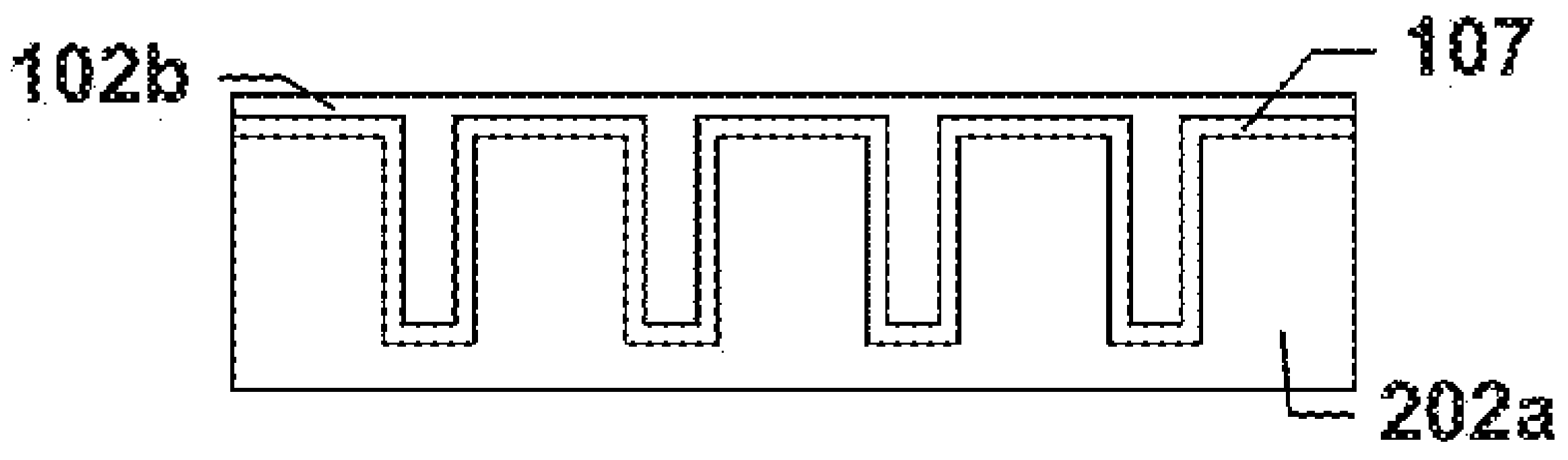

FIG. 11G

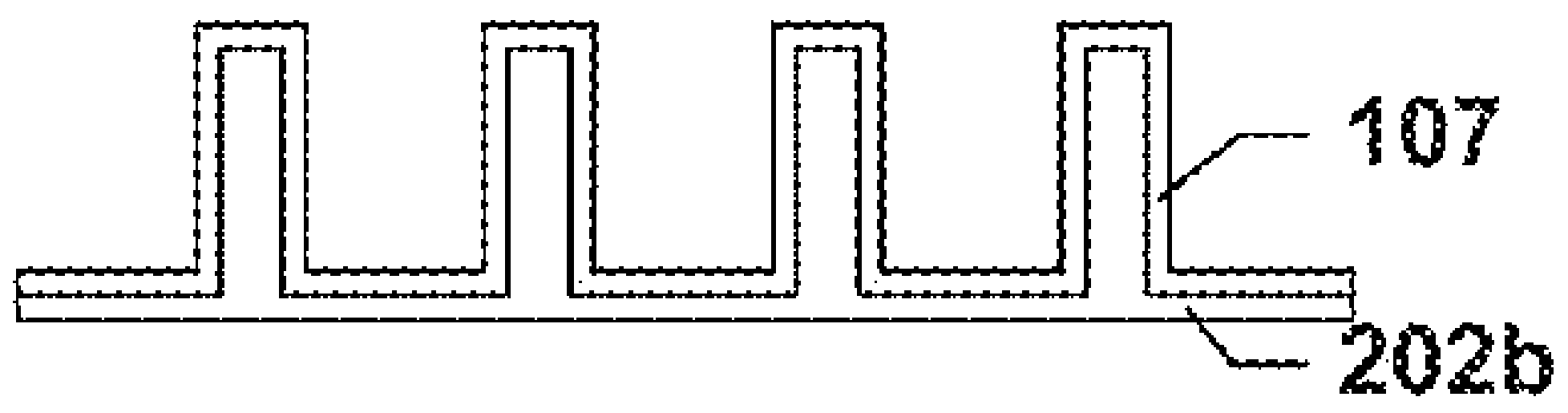

FIG. 11H

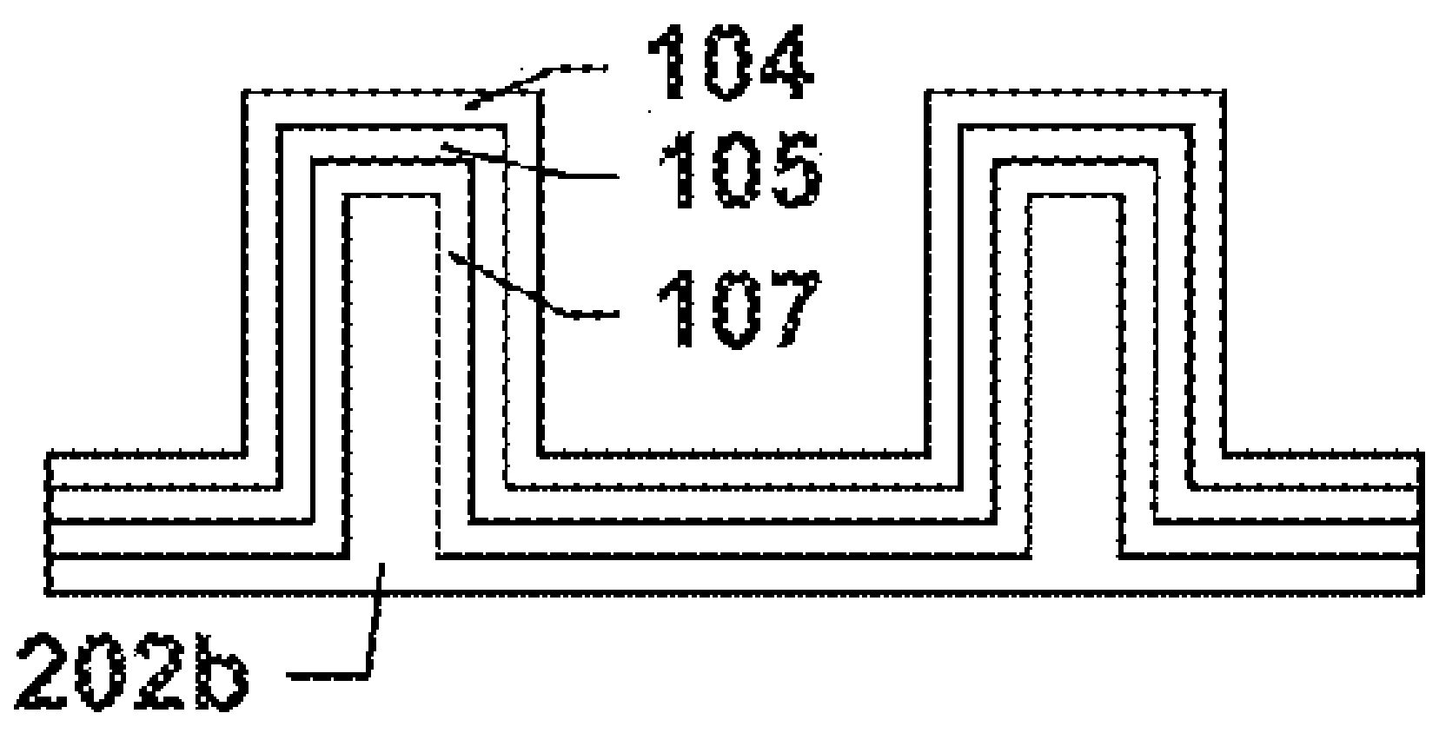

FIG. 11I

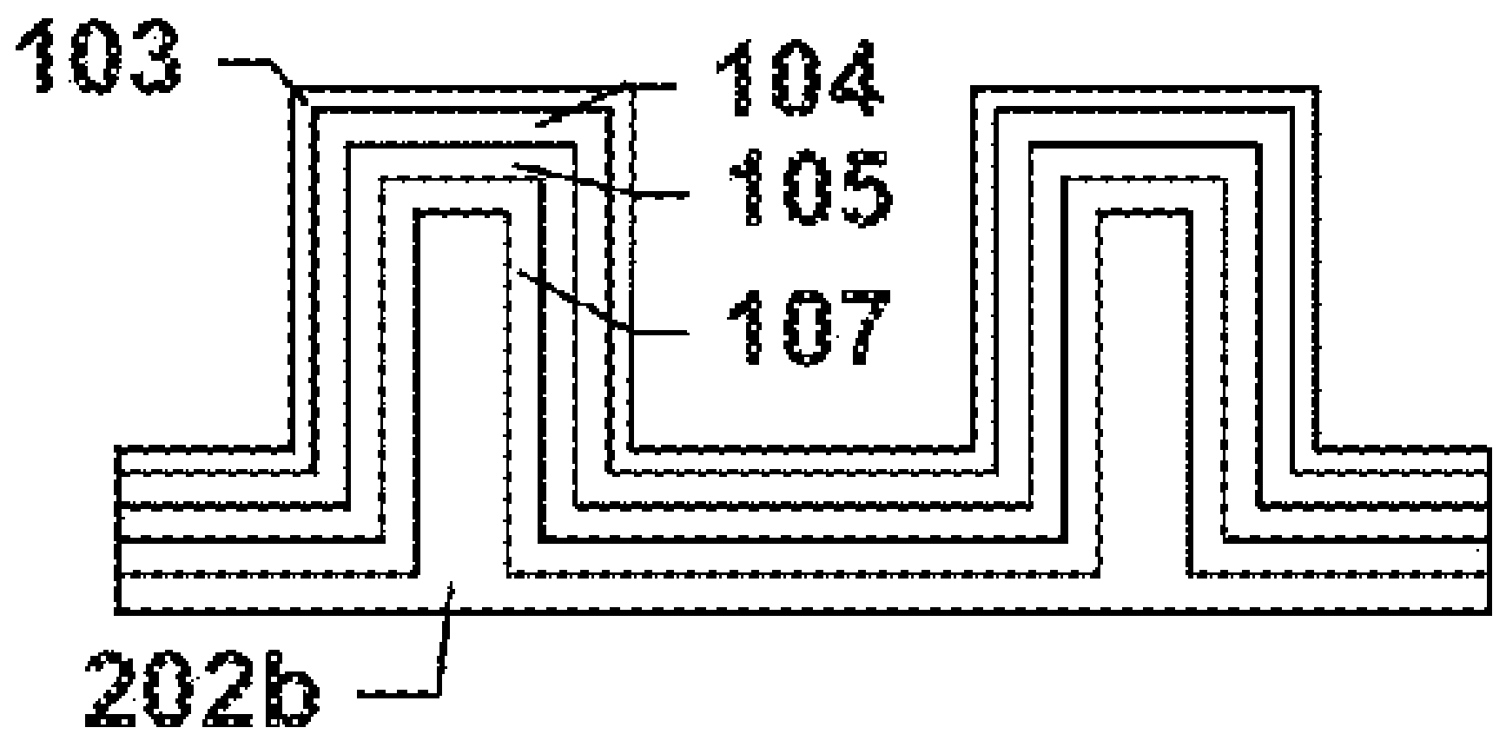

FIG. 11J

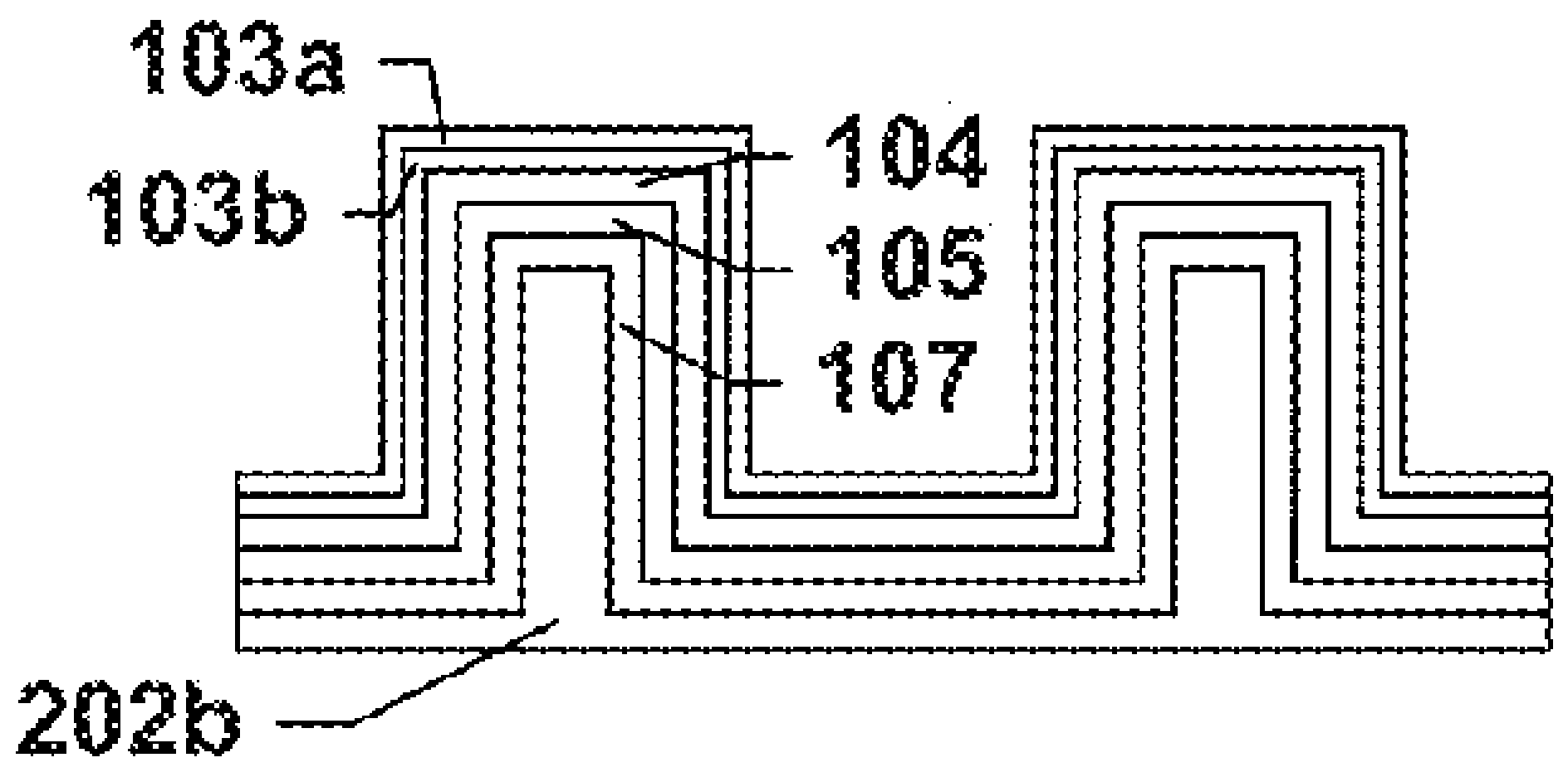

FIG. 11K

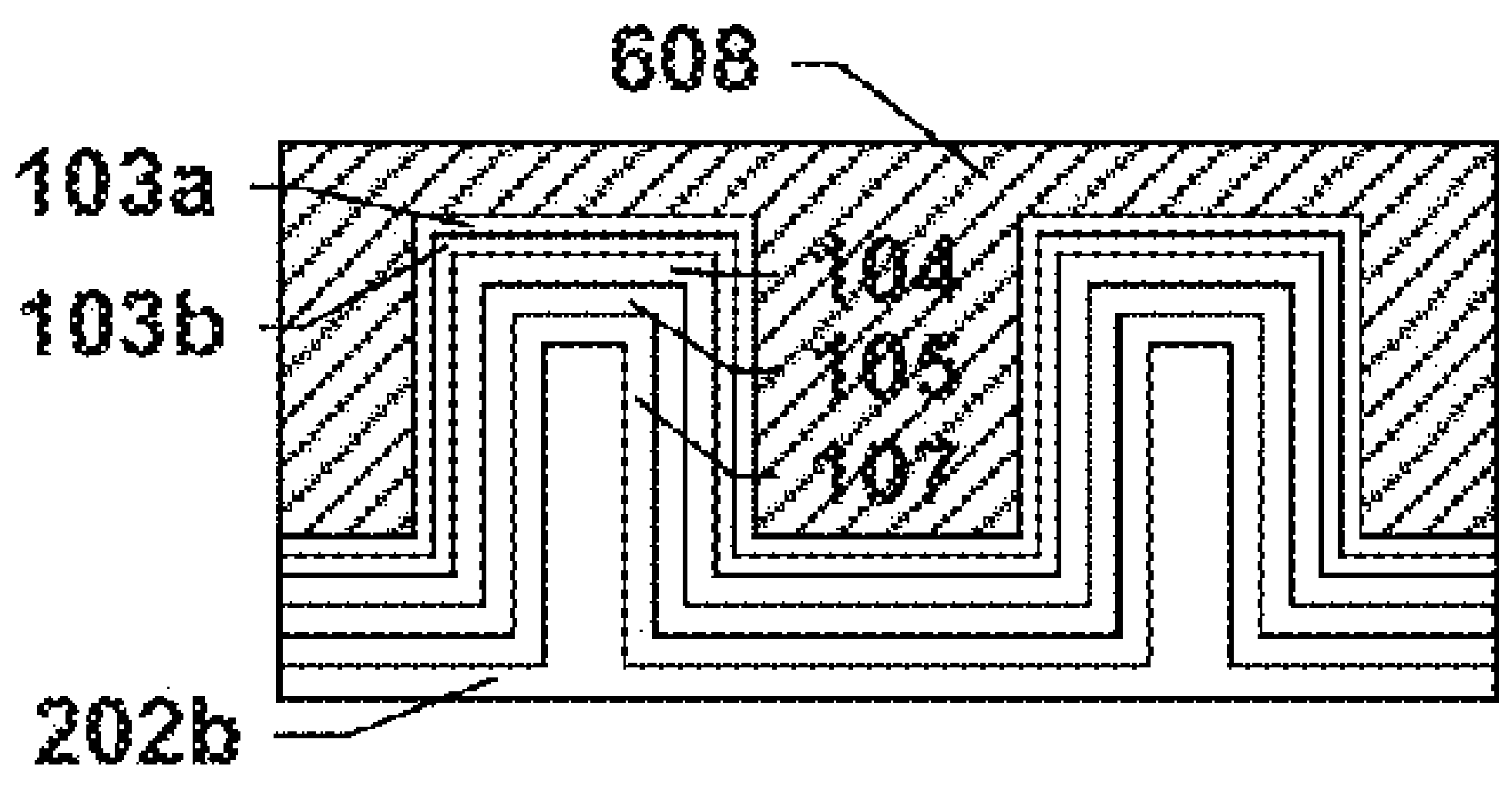

FIG. 11L

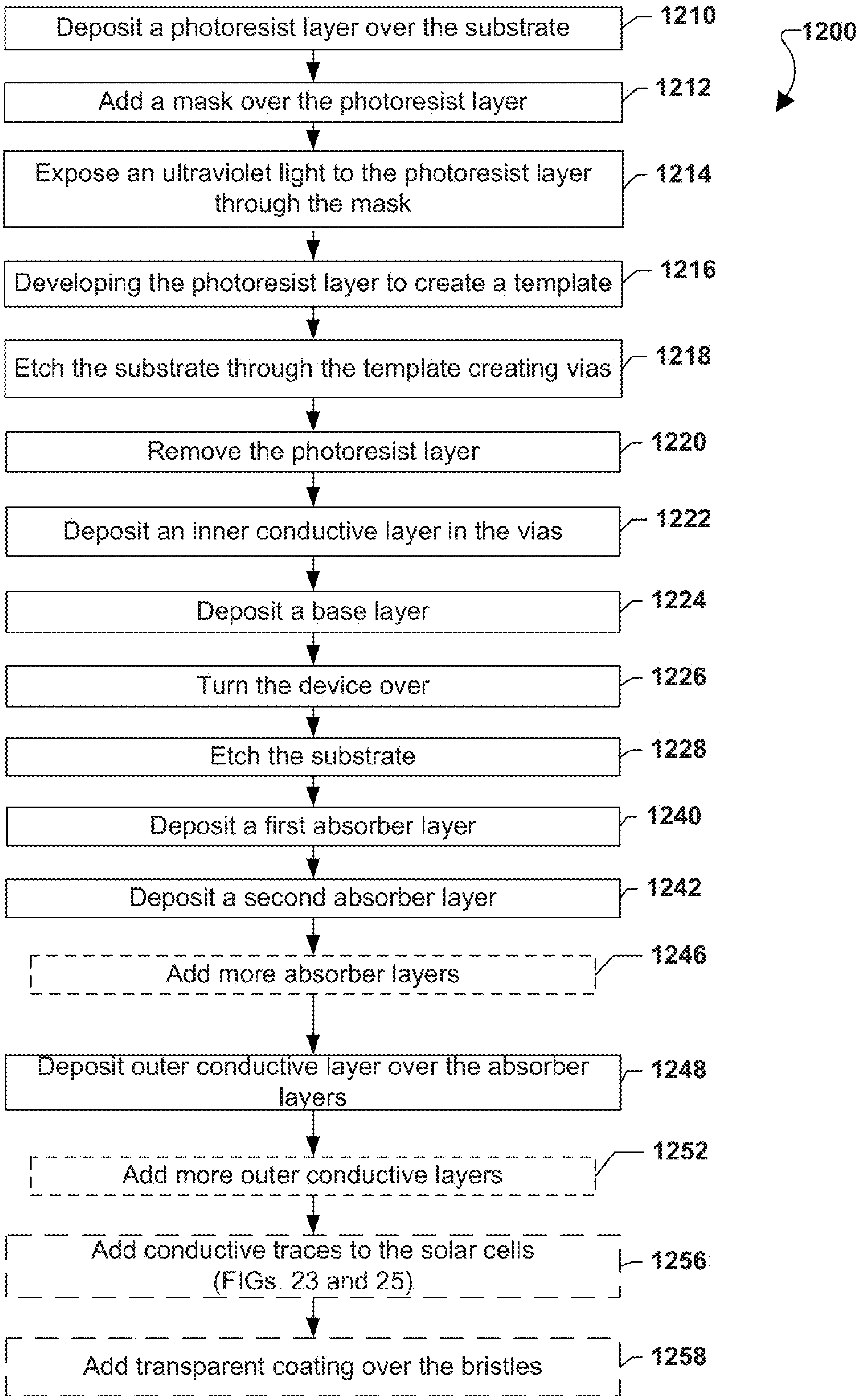
Deposit a photoresist layer over the substrate
1210
1200
Add a mask over the photoresist layer
1212
Expose an ultraviolet light to the photoresist layer through the mask
1214
Developing the photoresist layer to create a template
1216
Etch the substrate through the template creating vias
1218
Remove the photoresist layer
1220
Deposit an inner conductive layer in the vias
1222
Deposit a base layer
1224
Turn the device over
1226
Etch the substrate
1228
Deposit a first absorber layer
1240
Deposit a second absorber layer
1242
Add more absorber layers
1246
Deposit outer conductive layer over the absorber layers
1248
Add more outer conductive layers
1252
Add conductive traces to the solar cells (FIGs. 23 and 25)
1256
Add transparent coating over the bristles
1258

FIG. 12

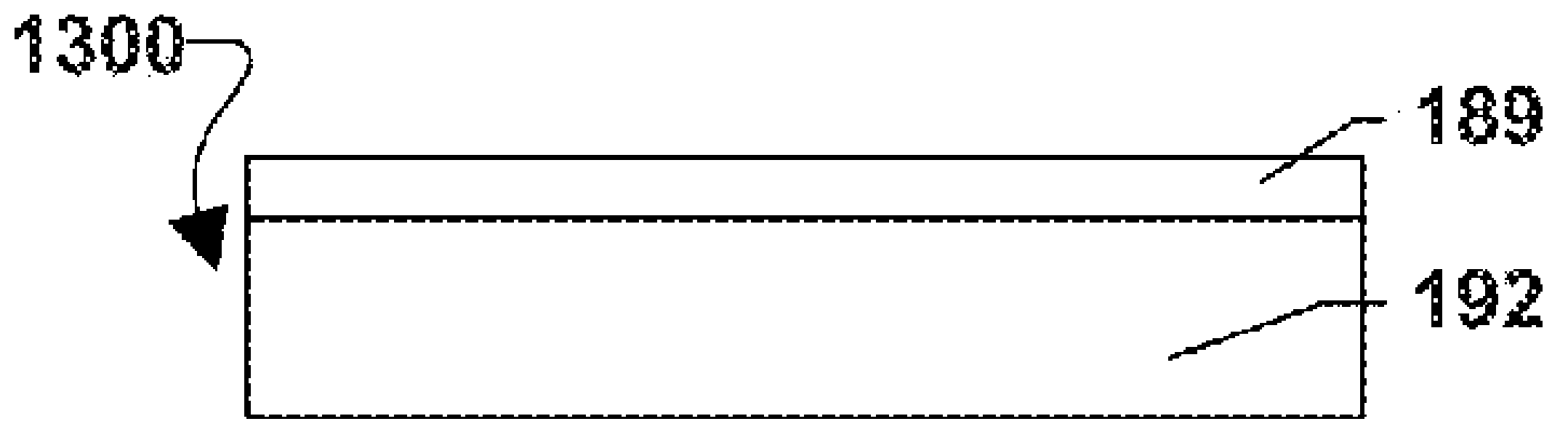

FIG. 13A

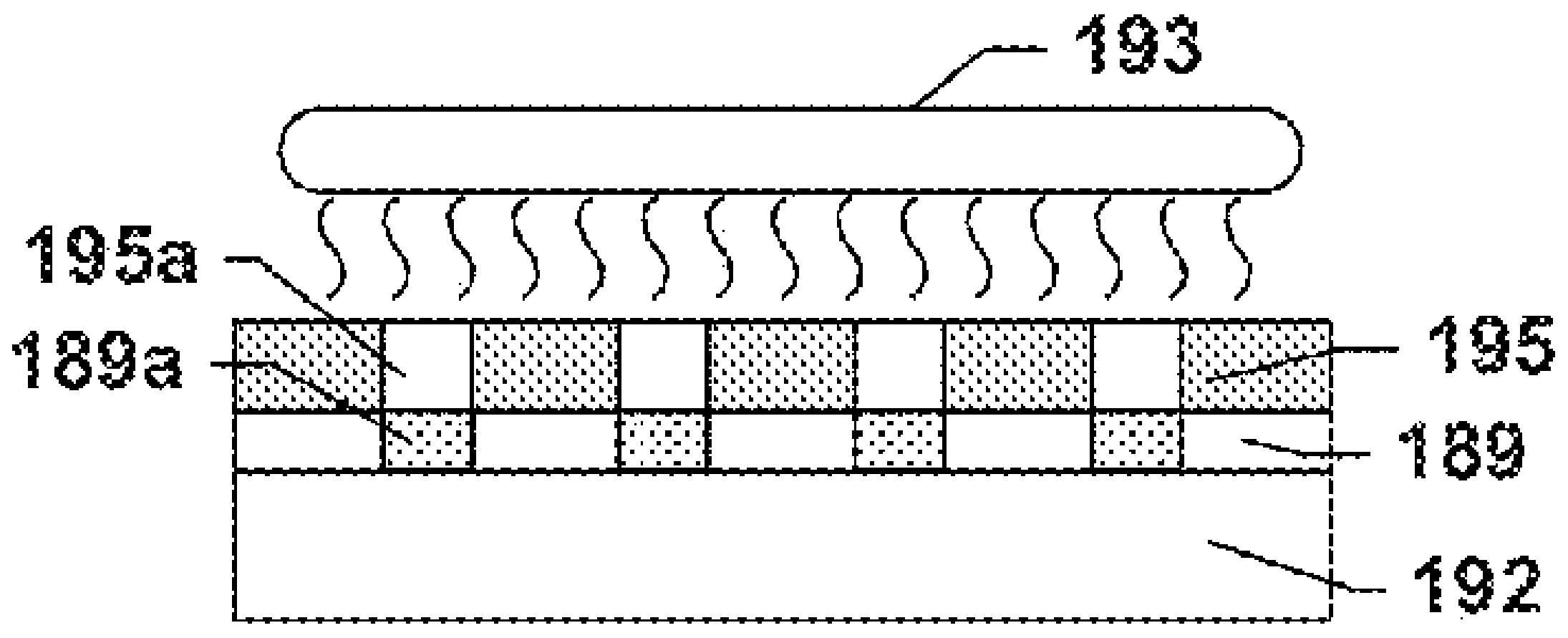

FIG. 13B

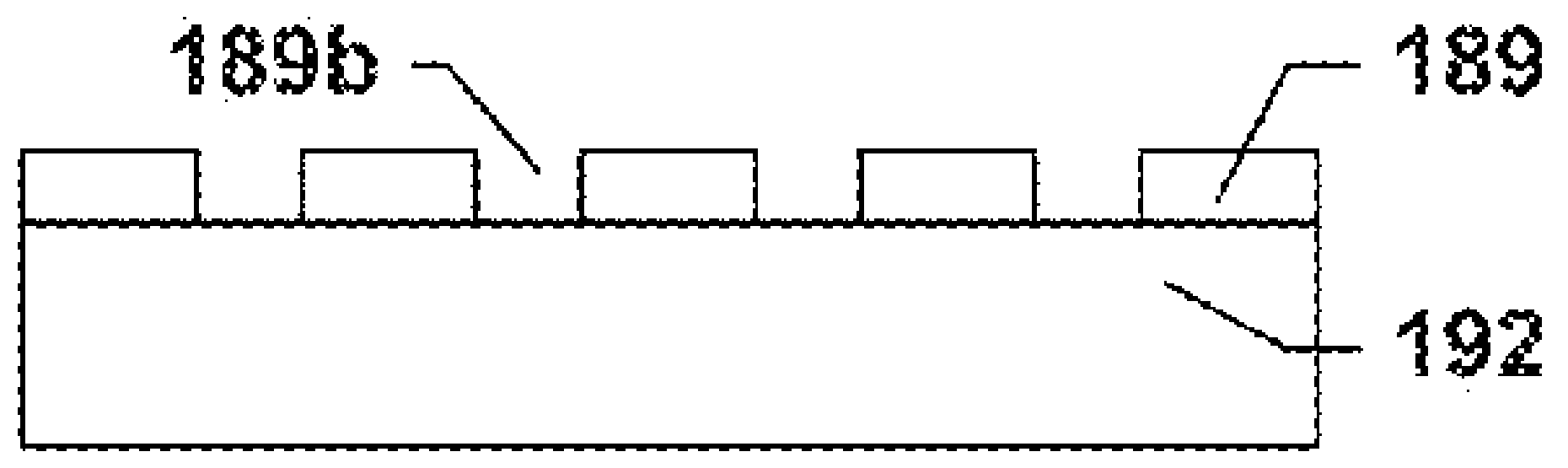

FIG. 13C

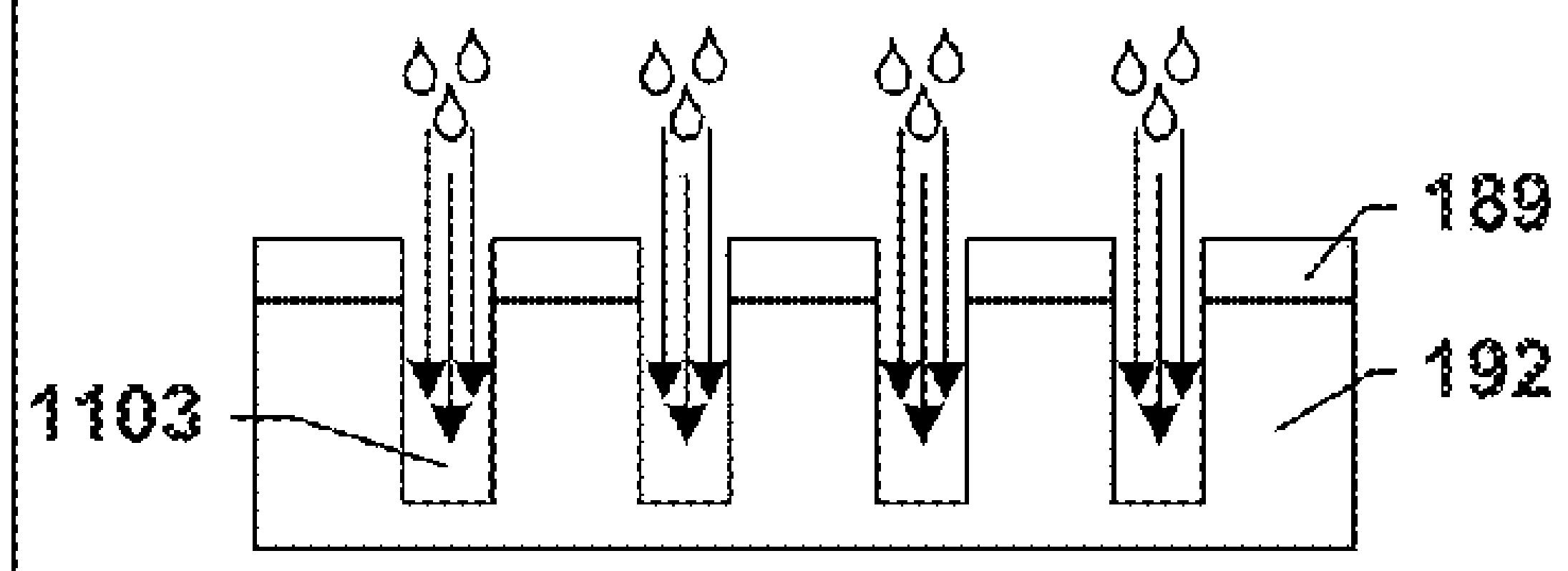

FIG. 13D

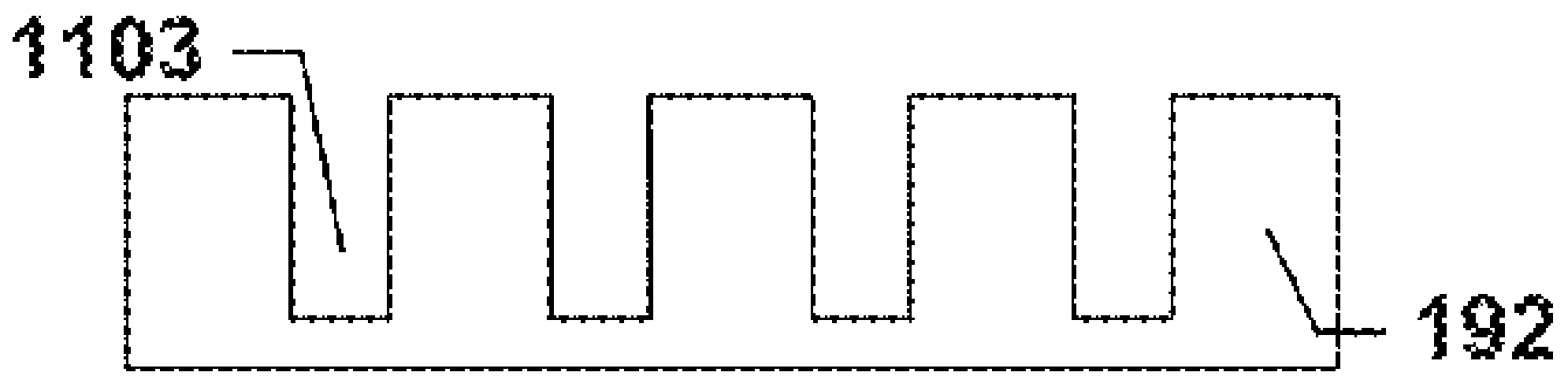

FIG. 13E

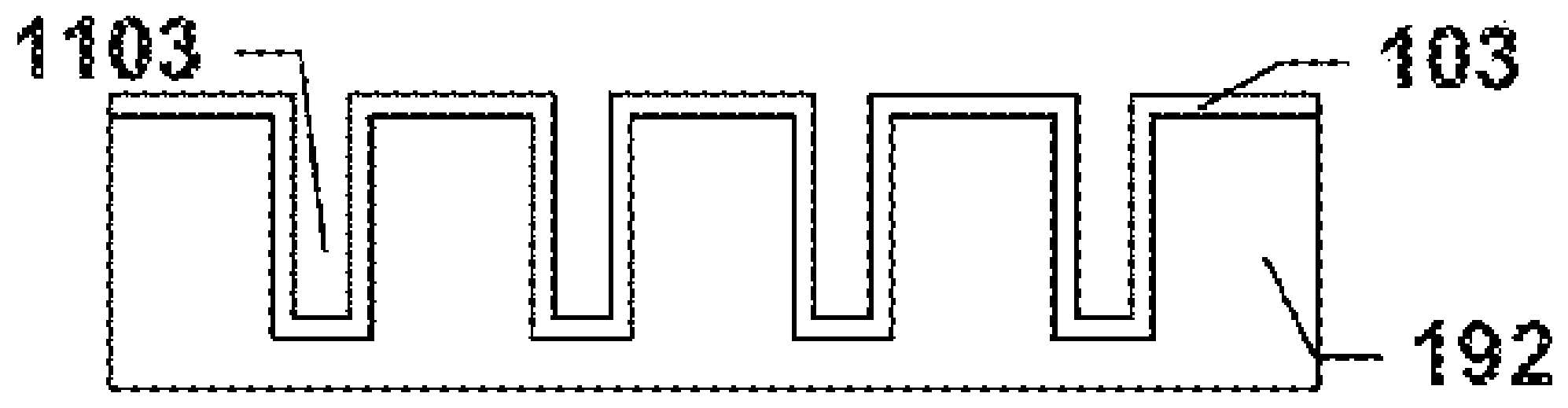

FIG. 13F

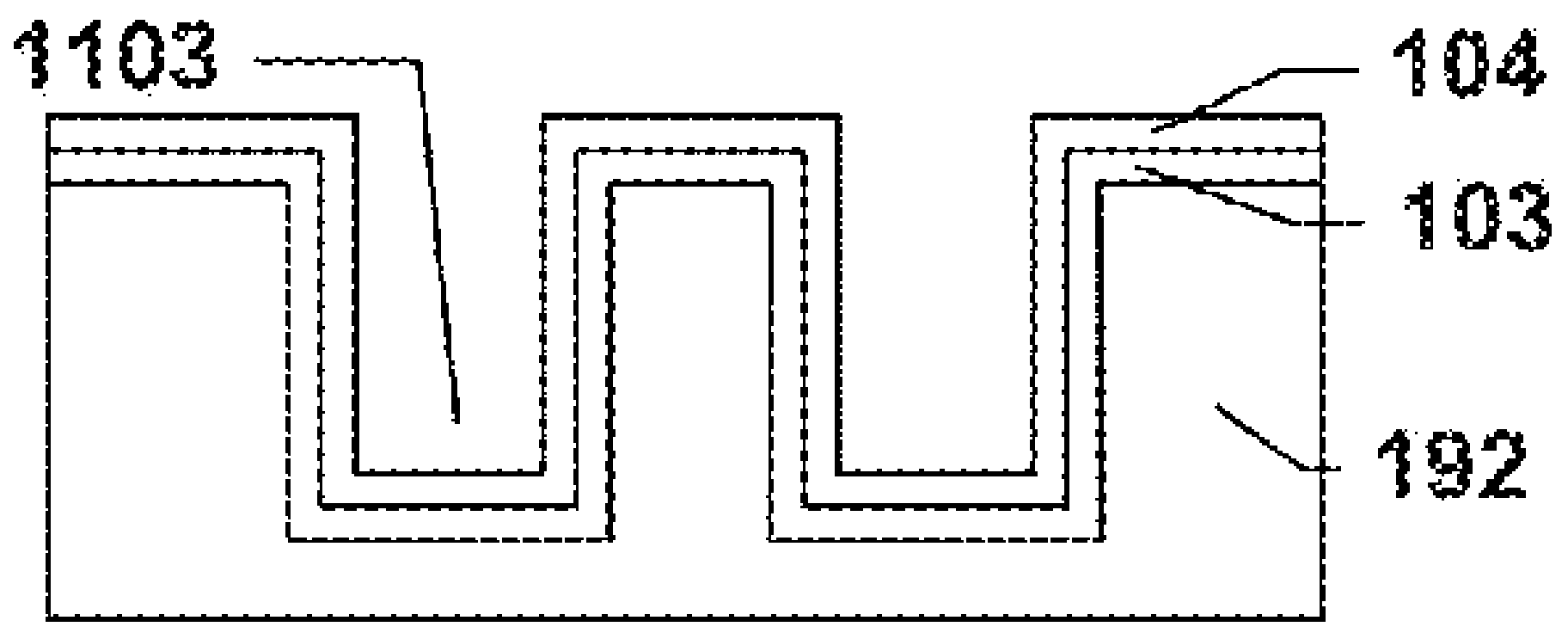

FIG. 13G

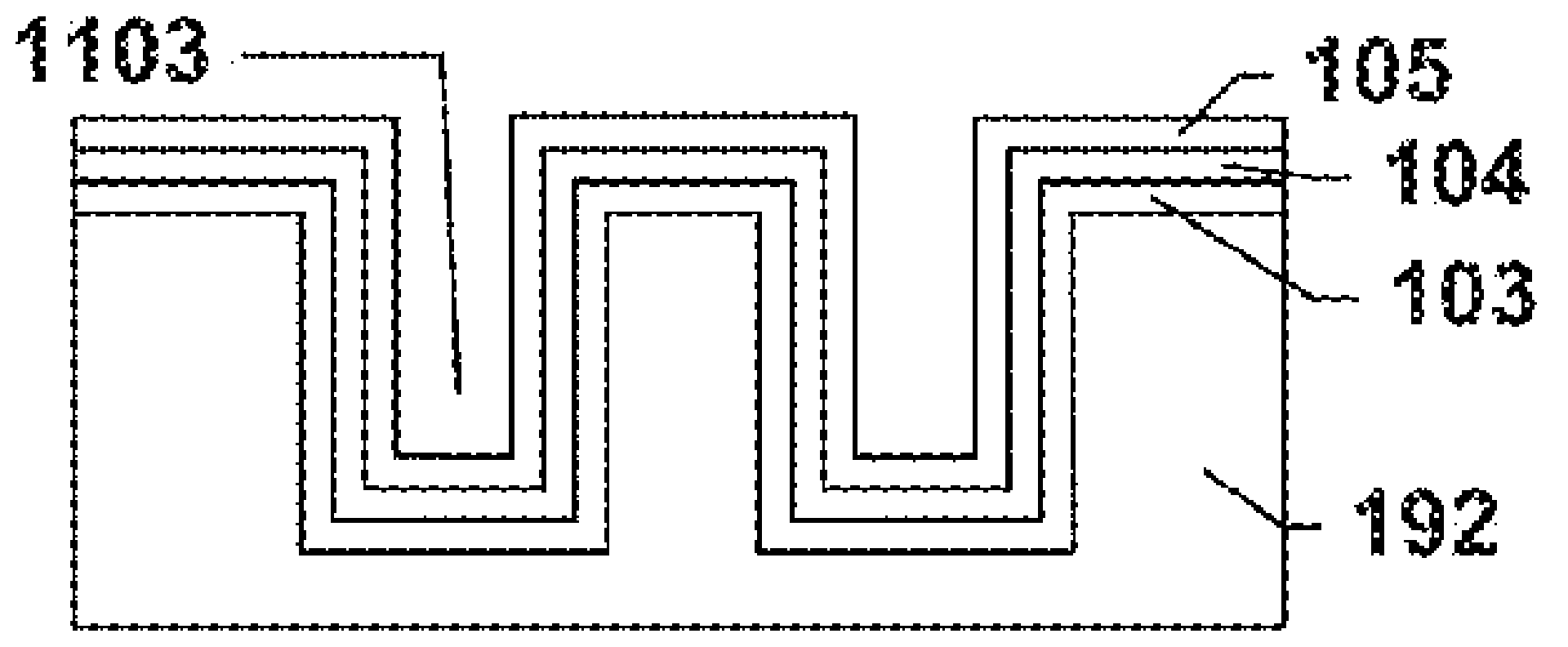

FIG. 13H

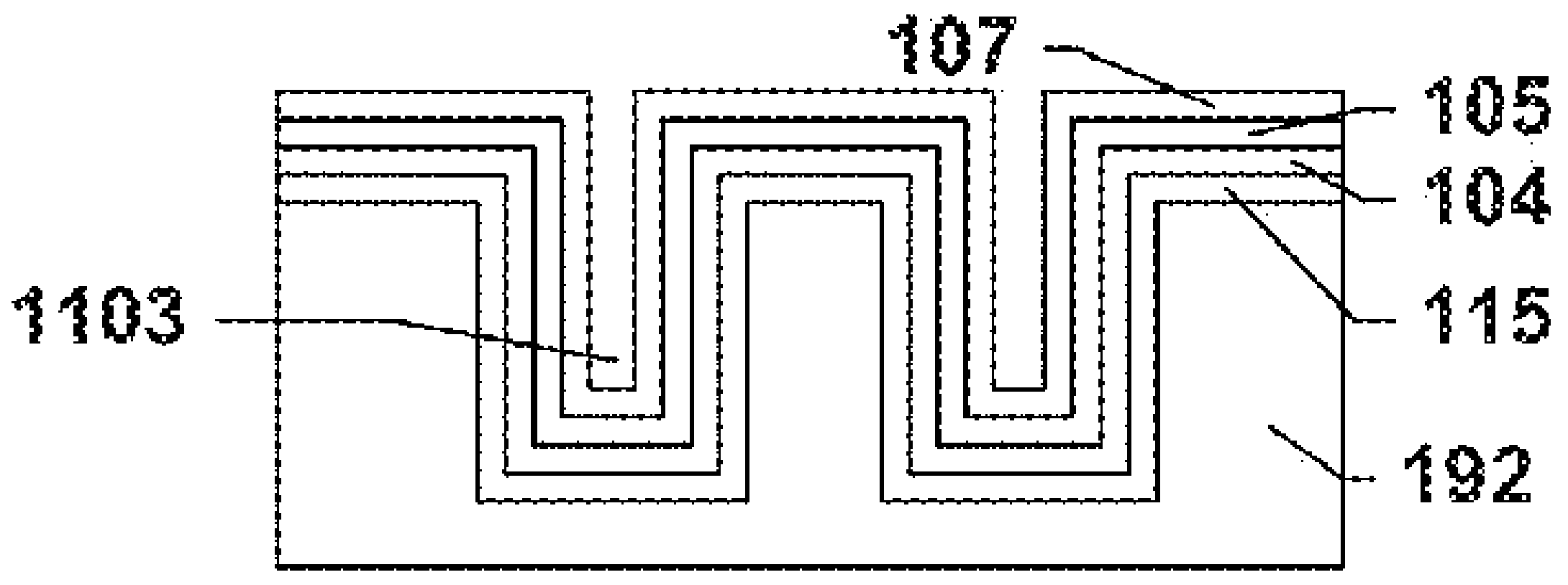

FIG. 13I

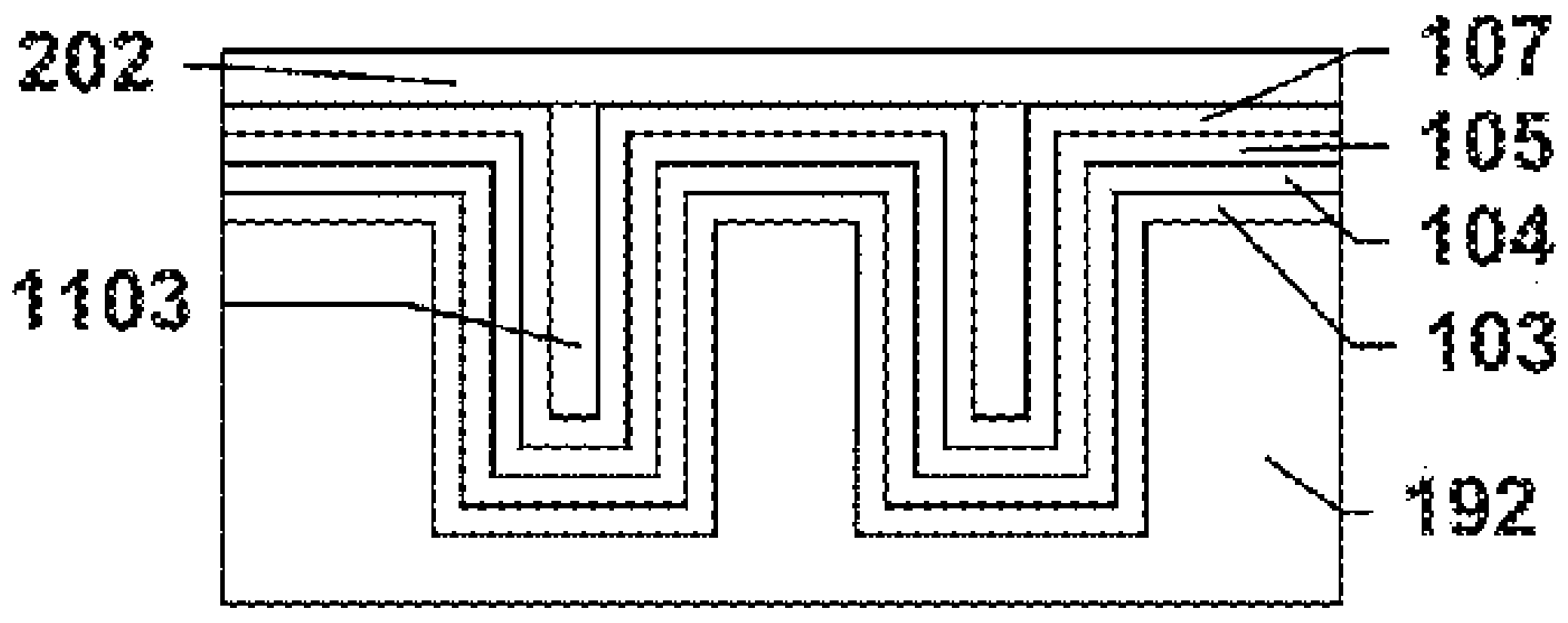

FIG. 13J

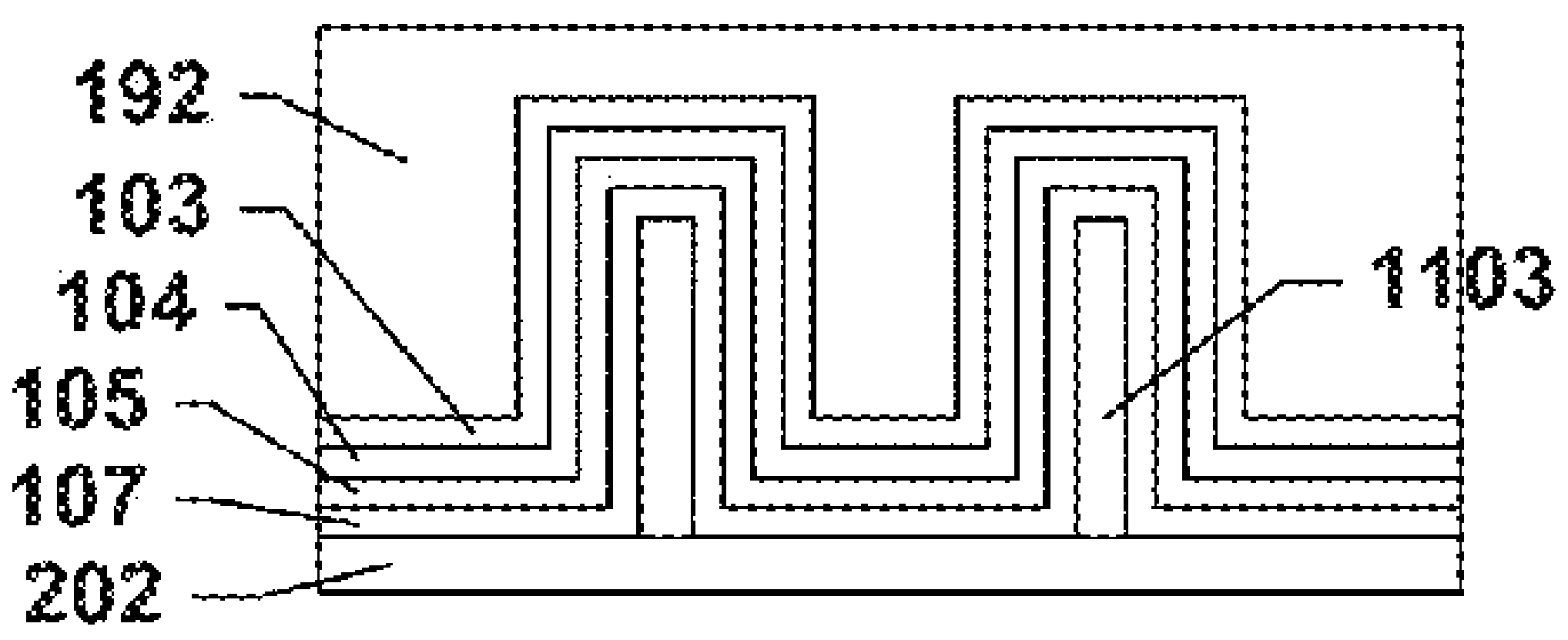

FIG. 13K

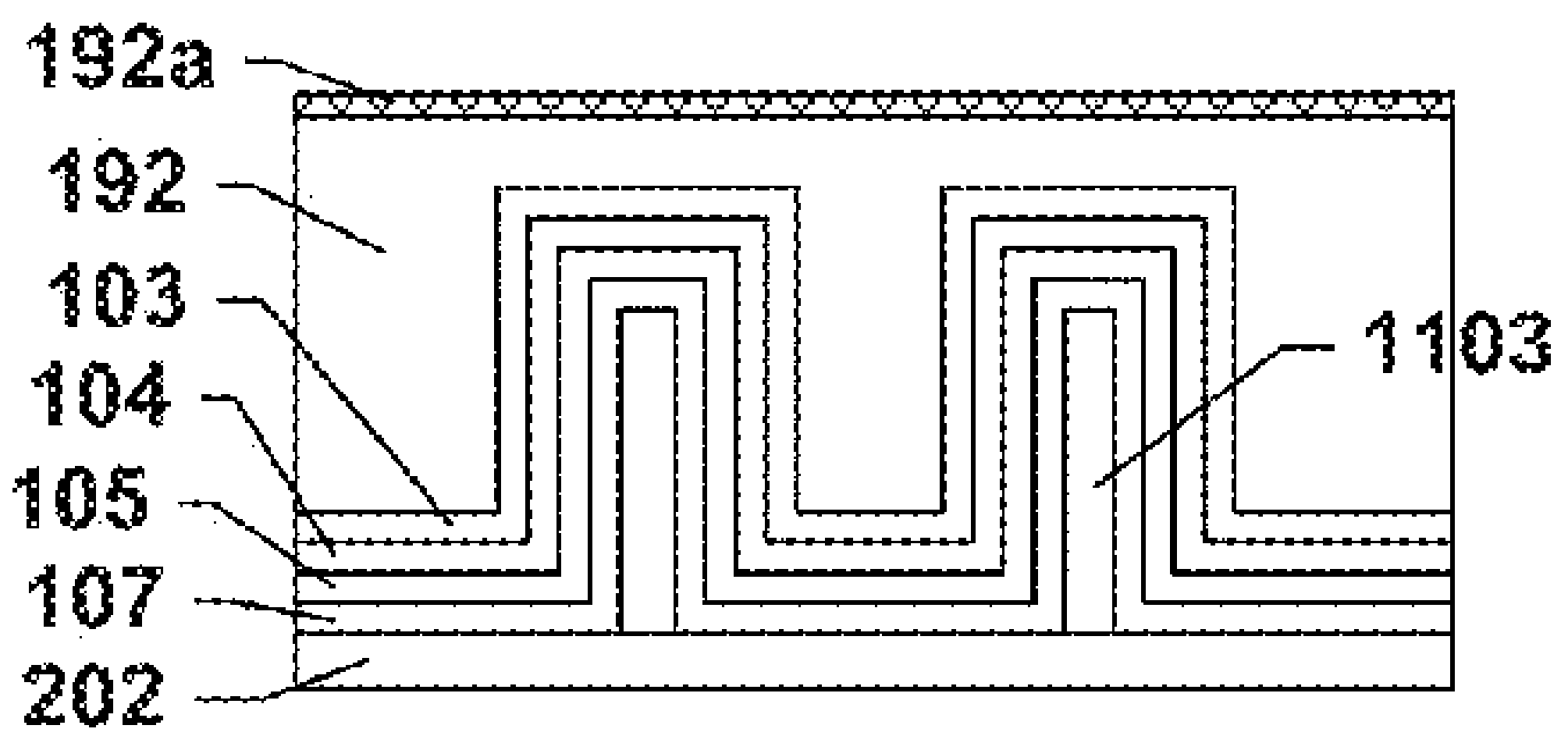

FIG. 13L

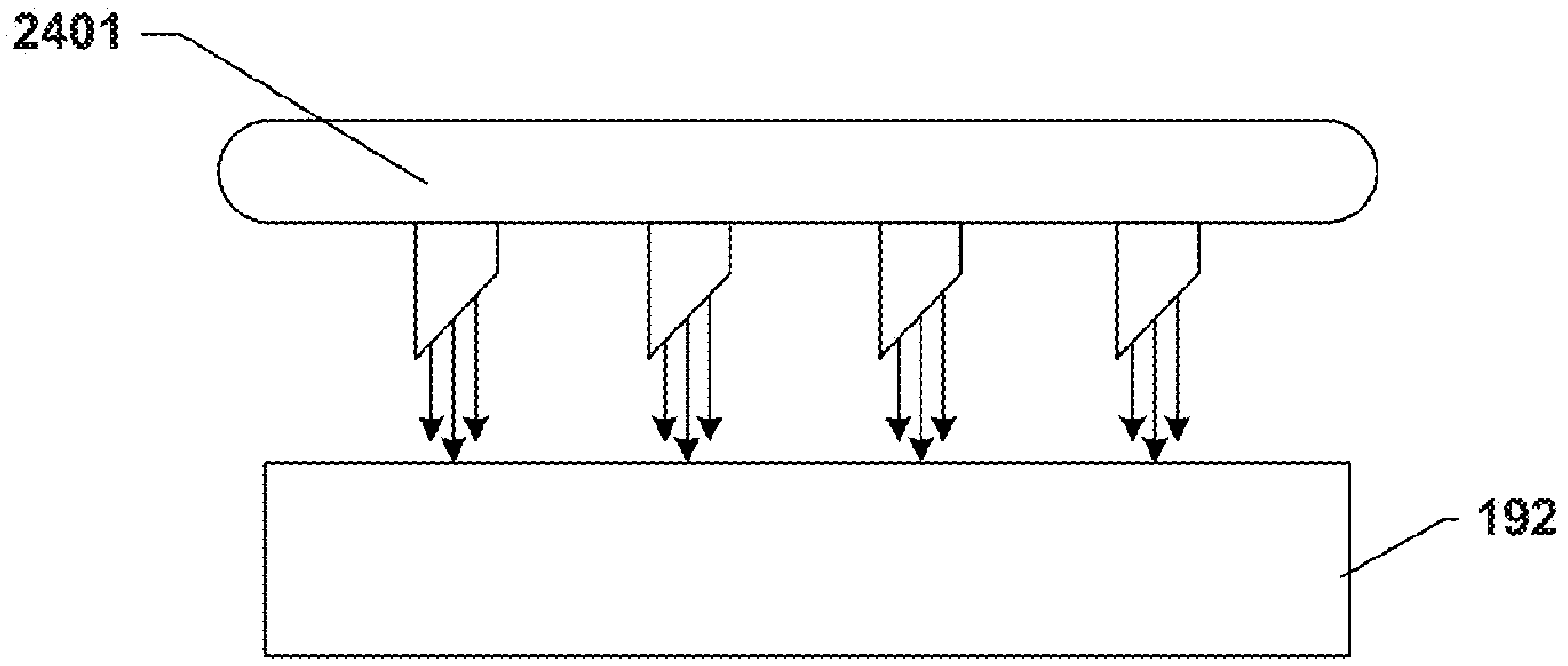

FIG. 13M

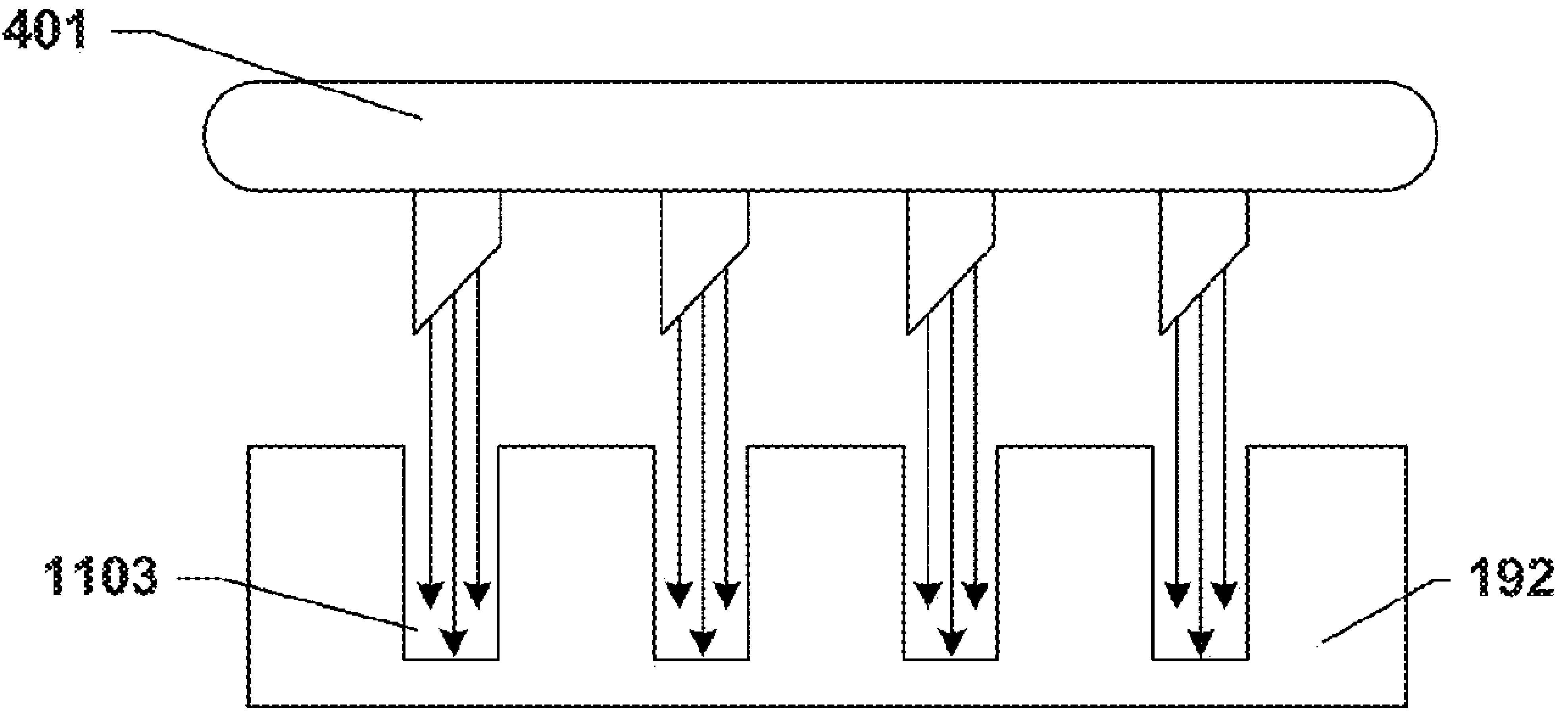

FIG. 13N

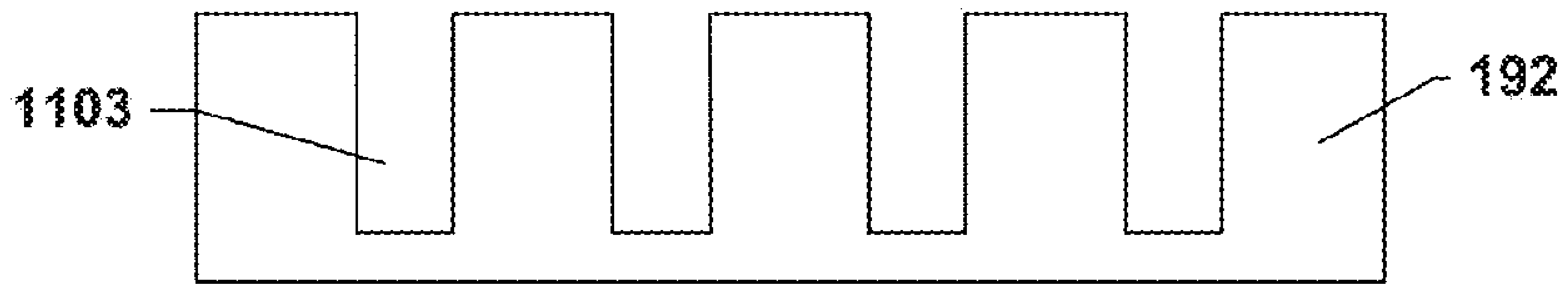

FIG. 13O

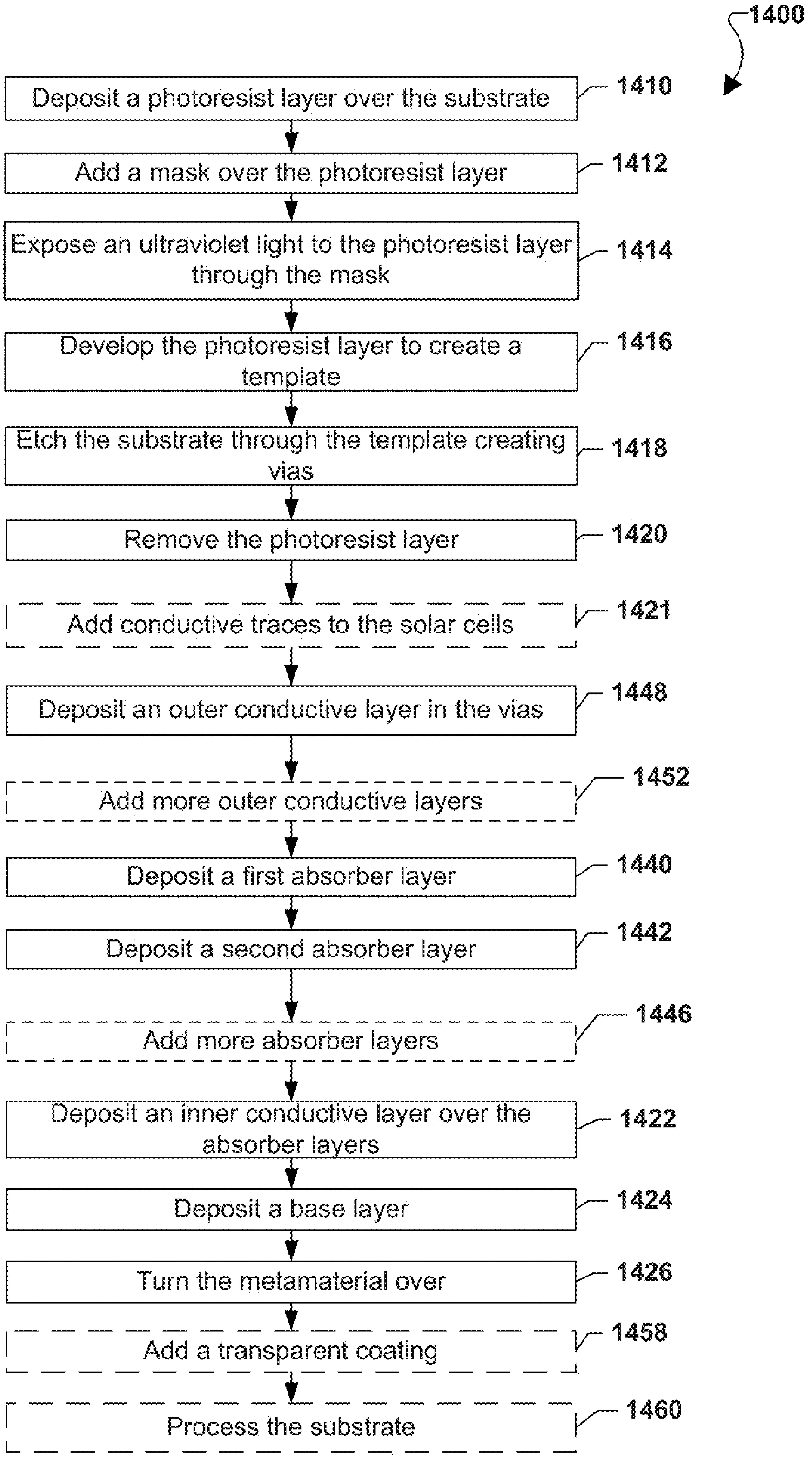
1400
Deposit a photoresist layer over the substrate
1410
Add a mask over the photoresist layer
1412
Expose an ultraviolet light to the photoresist layer through the mask
1414
Develop the photoresist layer to create a template
1416
Etch the substrate through the template creating vias
1418
Remove the photoresist layer
1420
Add conductive traces to the solar cells
1421
Deposit an outer conductive layer in the vias
1448
Add more outer conductive layers
1452
Deposit a first absorber layer
1440
Deposit a second absorber layer
1442
Add more absorber layers
1446
Deposit an inner conductive layer over the absorber layers
1422
Deposit a base layer
1424
Turn the metamaterial over
1426
Add a transparent coating
1458
Process the substrate
1460

FIG. 14

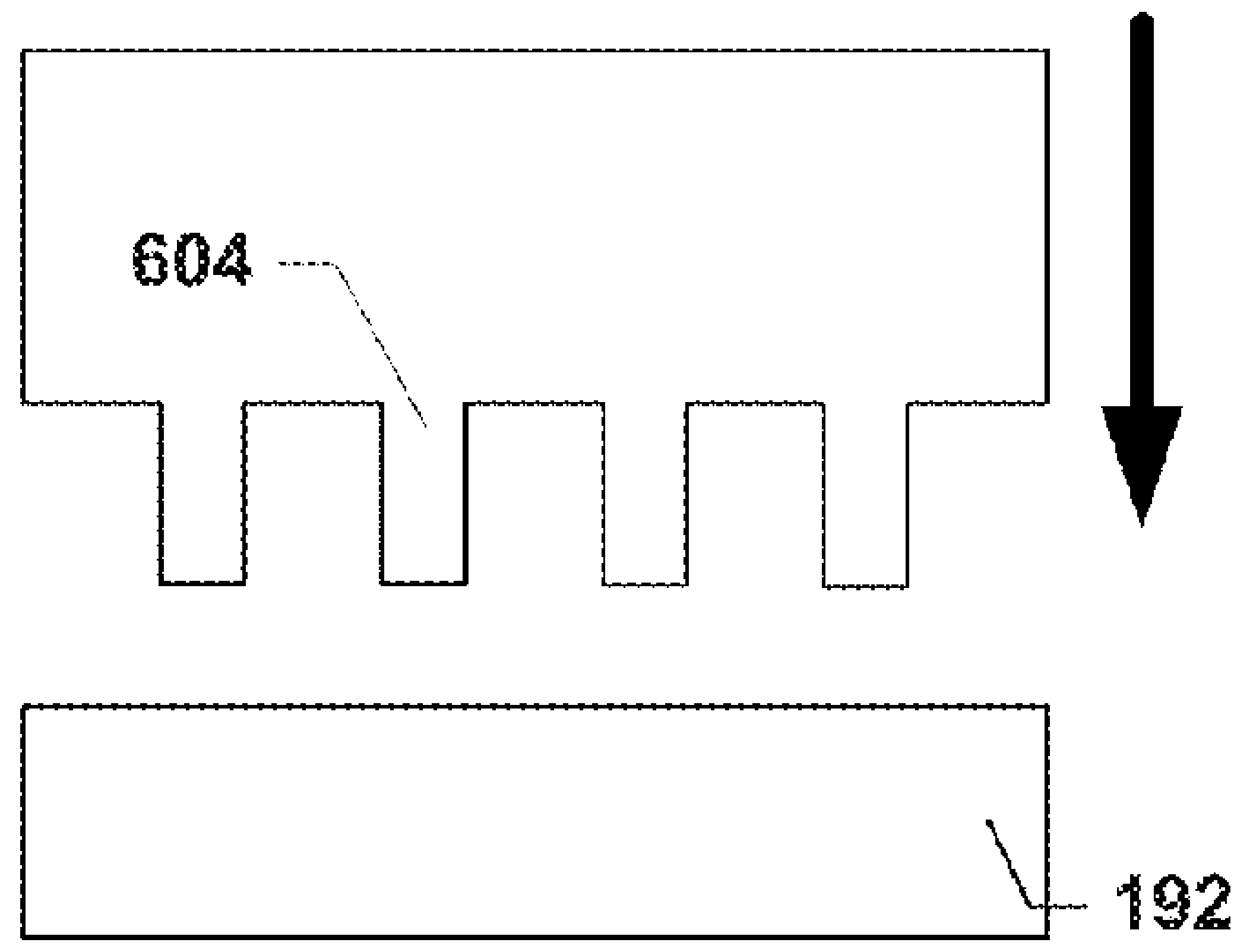

FIG. 15A

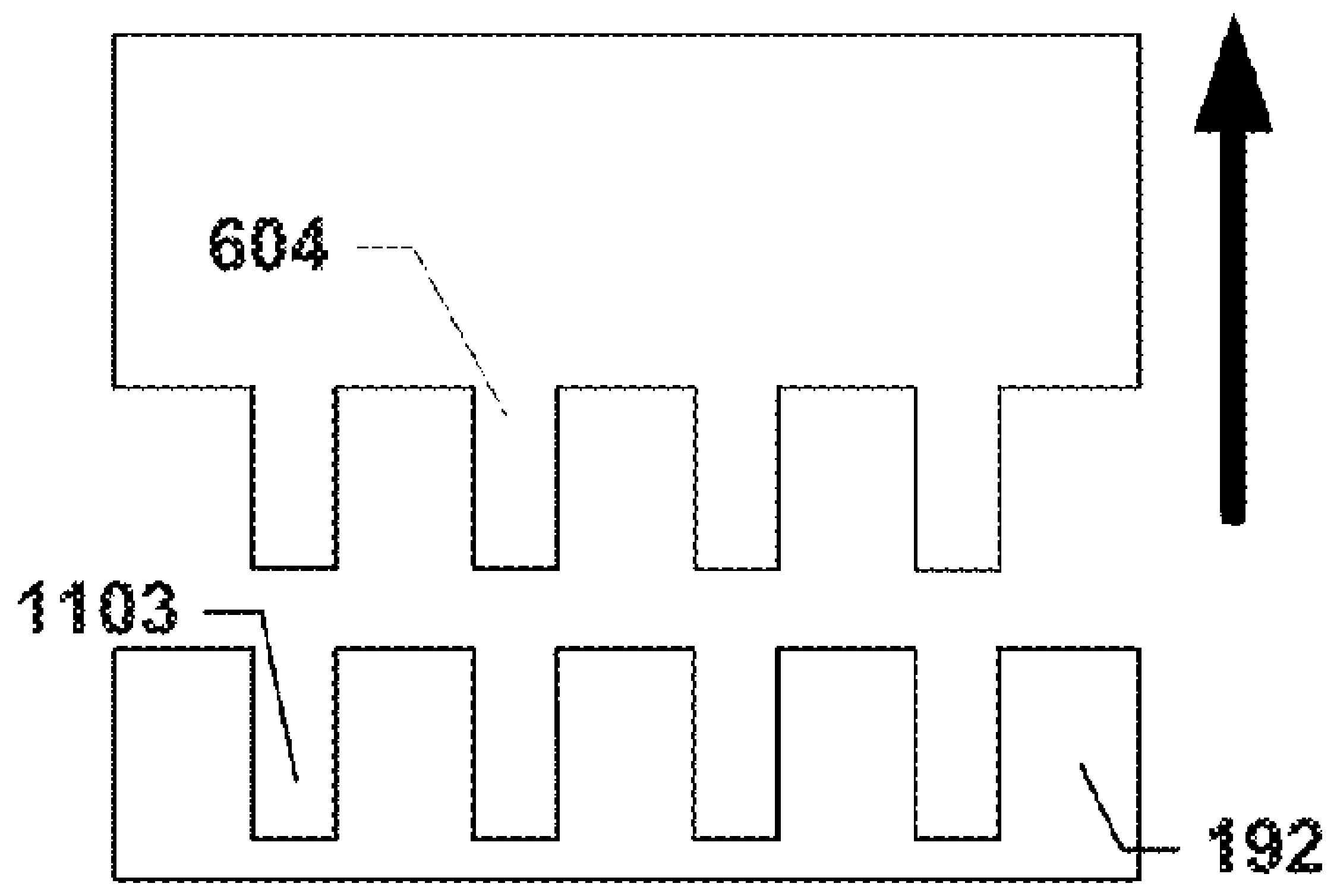

FIG. 15B

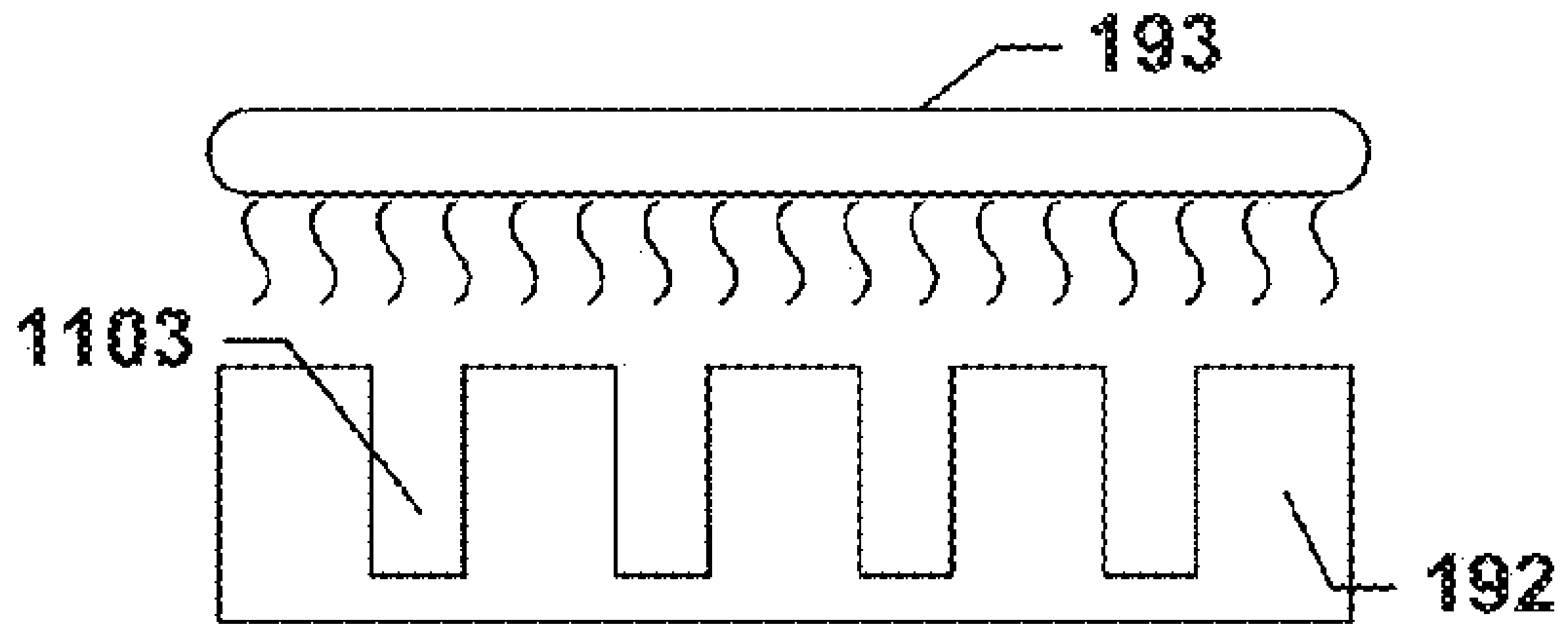

FIG. 15C

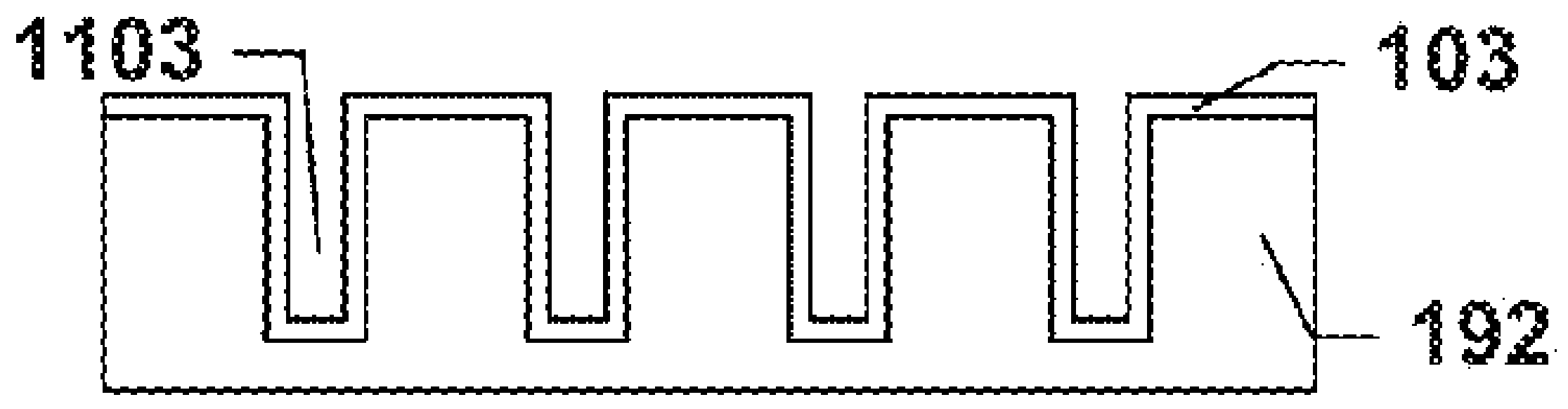

FIG. 15D

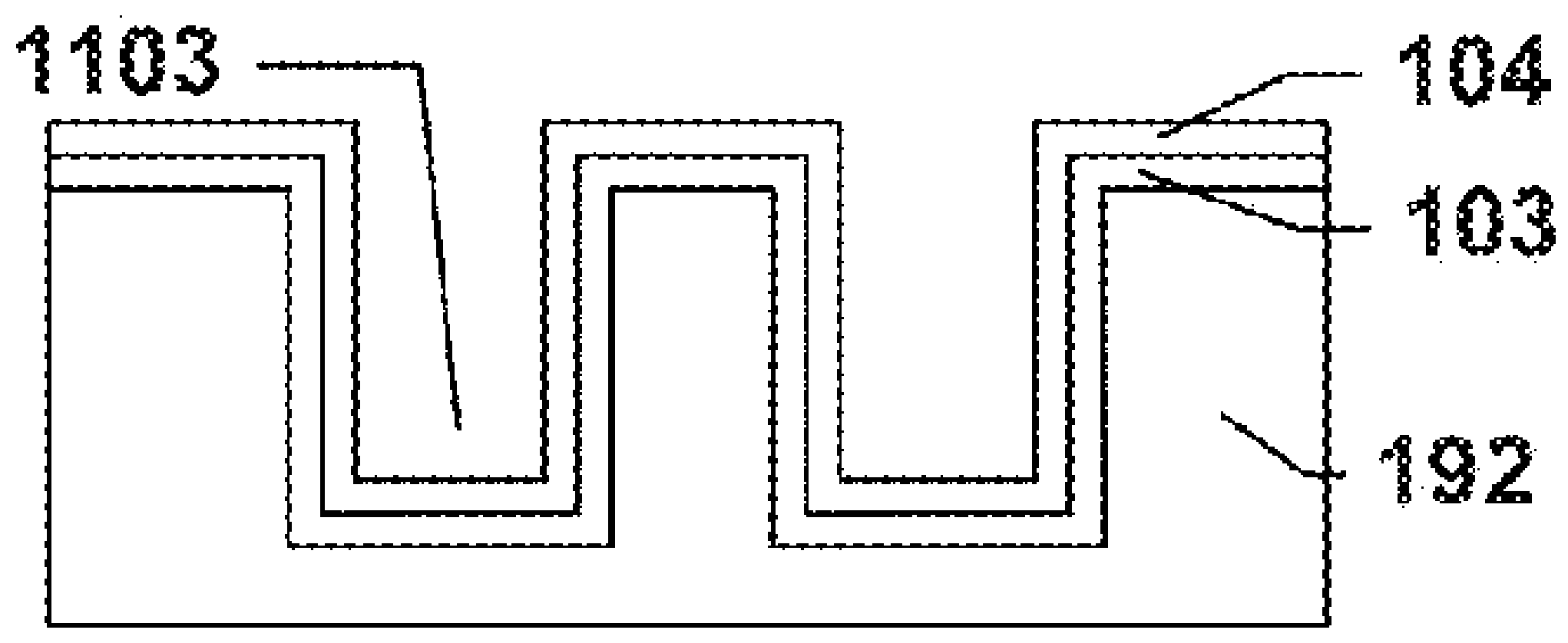

FIG. 15E

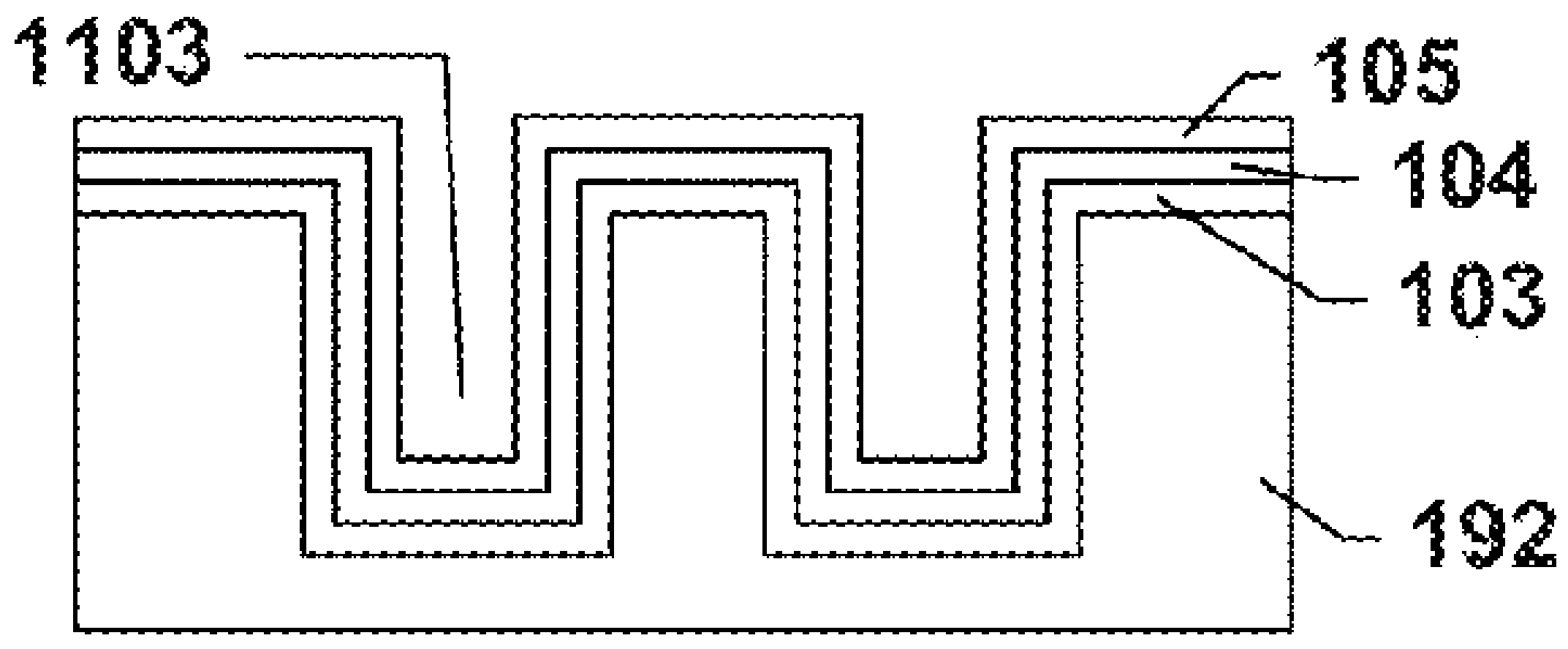

FIG. 15F

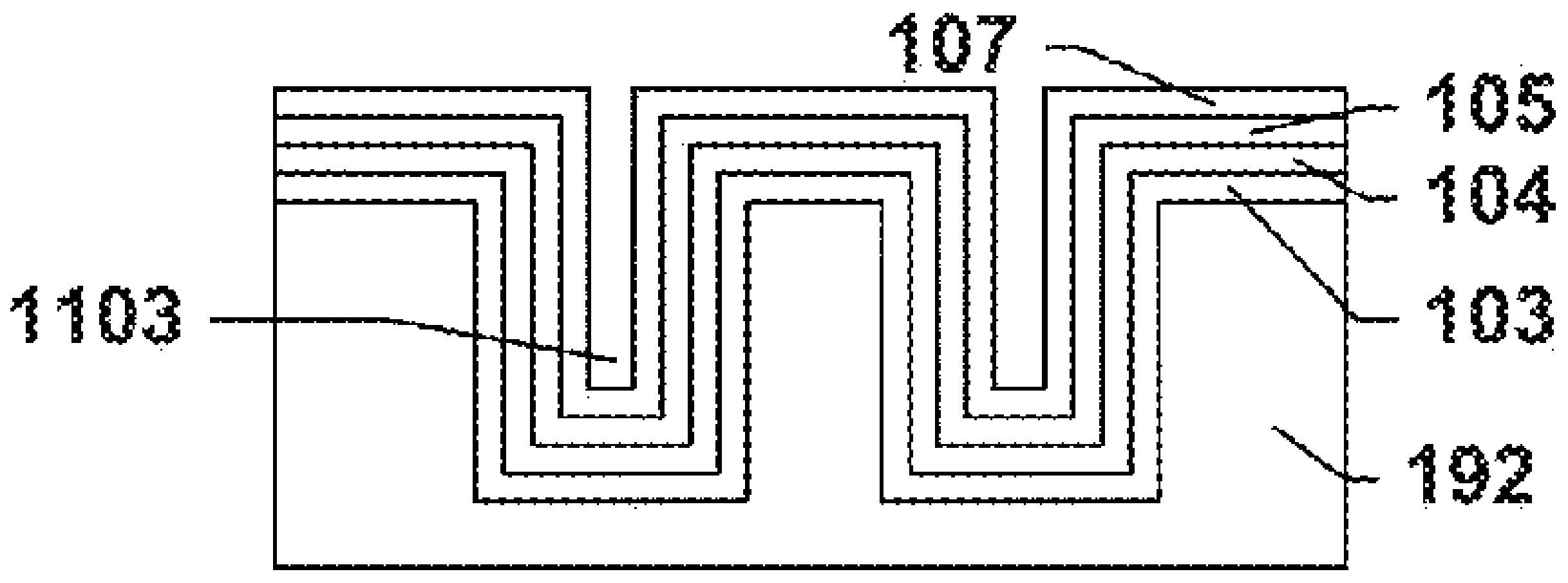

FIG. 15G

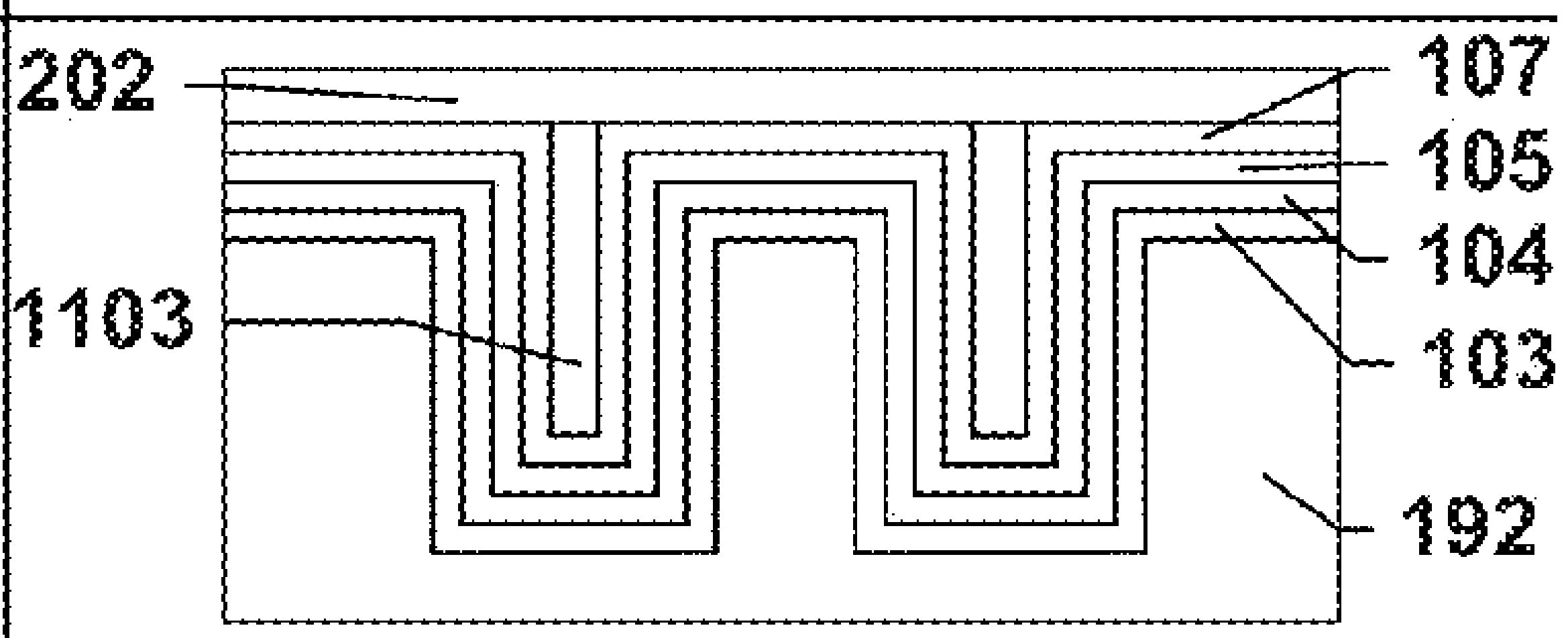

FIG. 15H

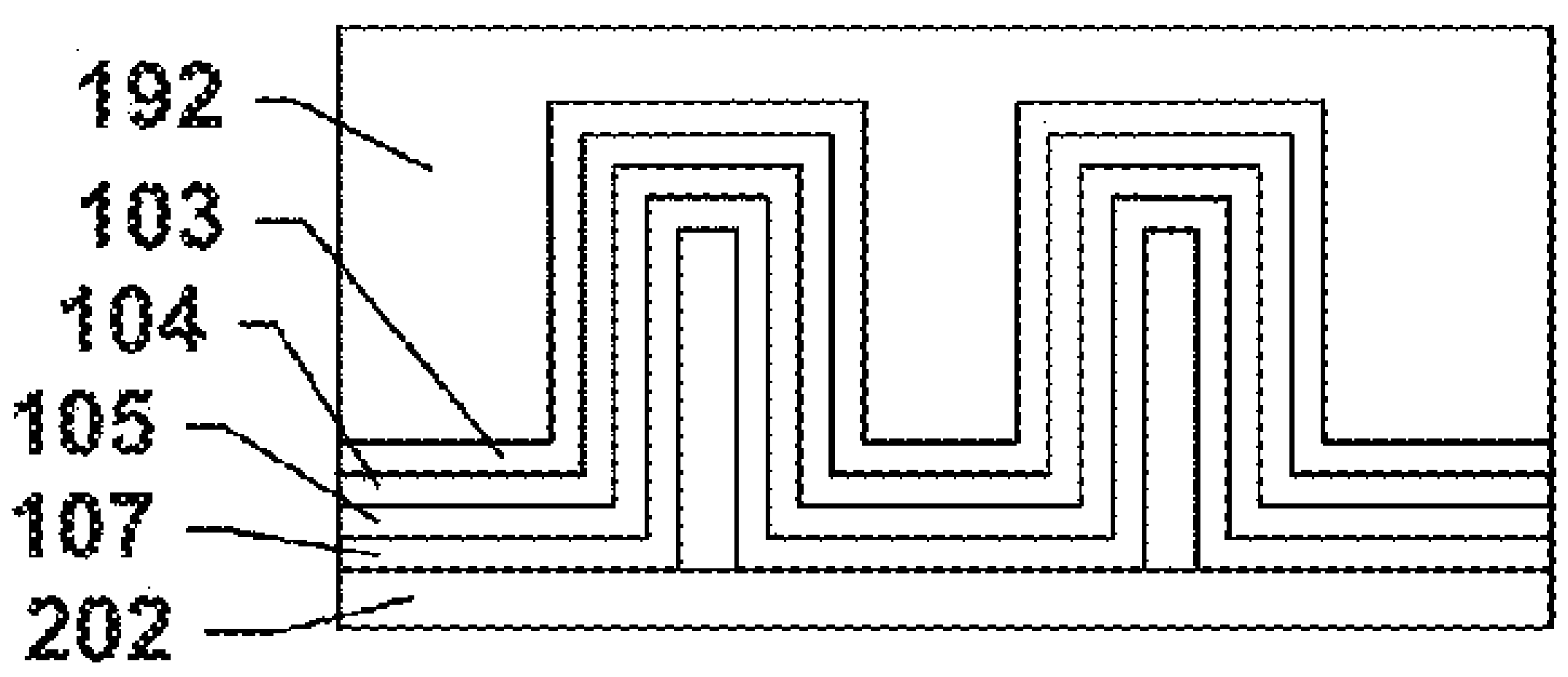

FIG. 15I

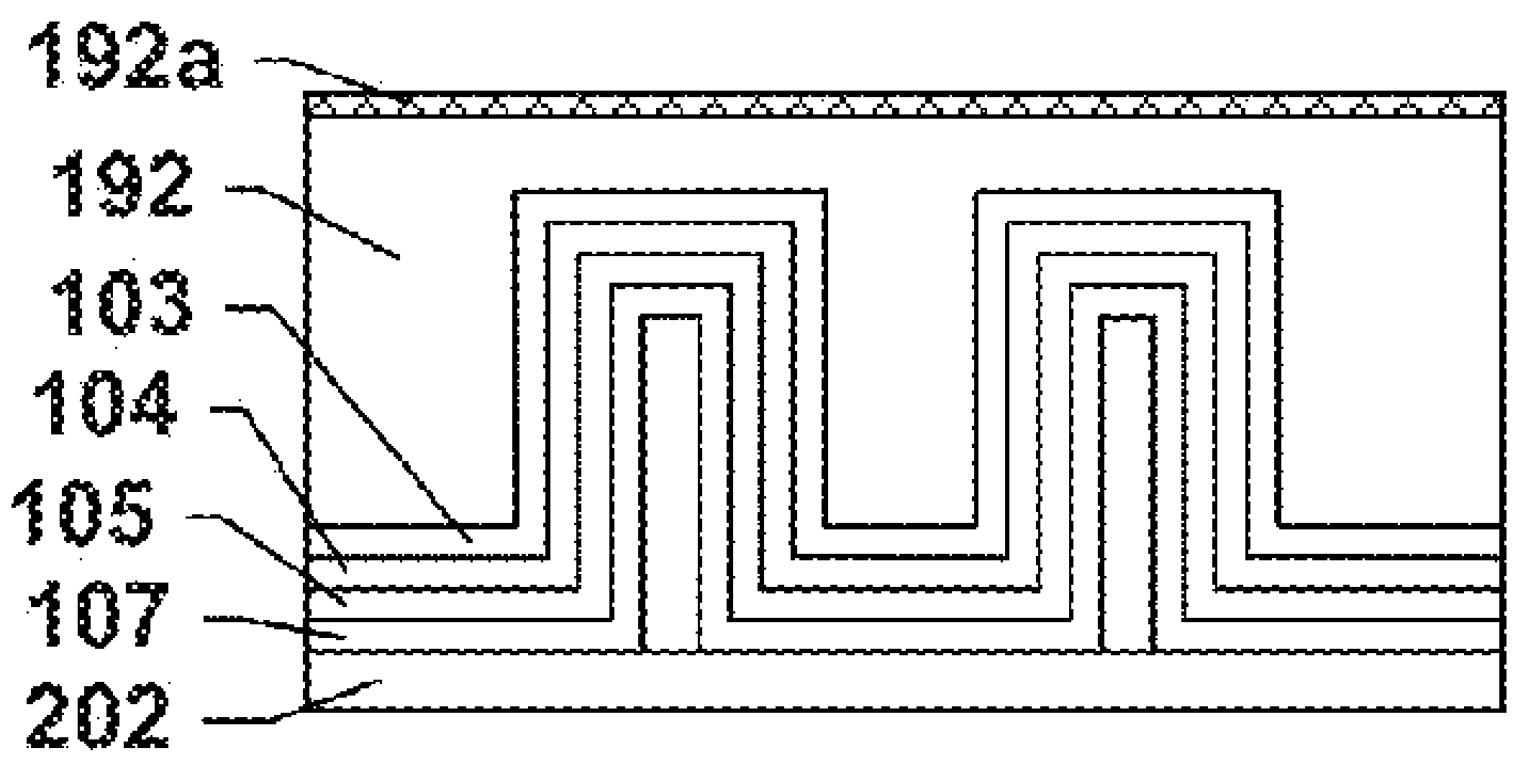

FIG. 15J

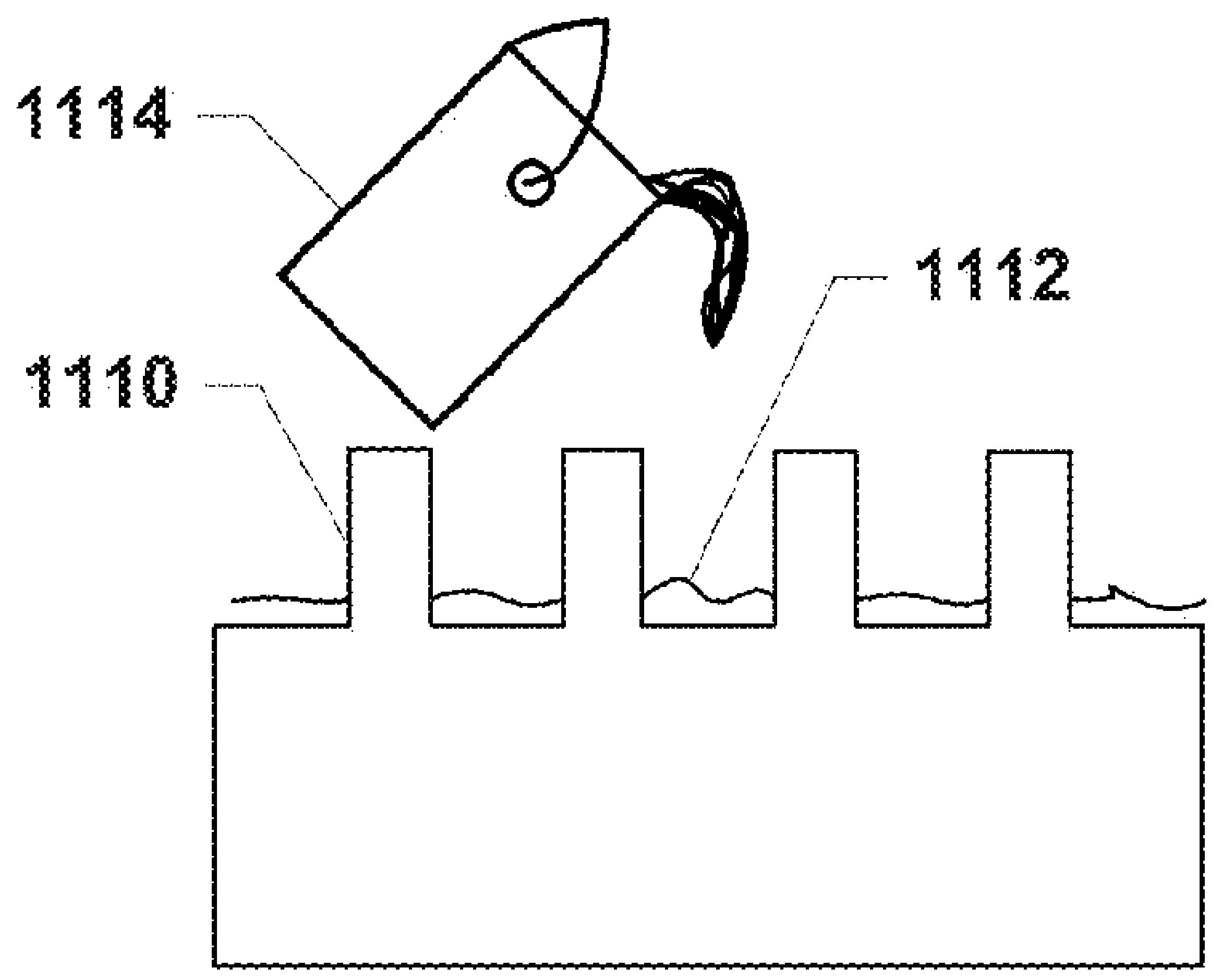

FIG. 15K

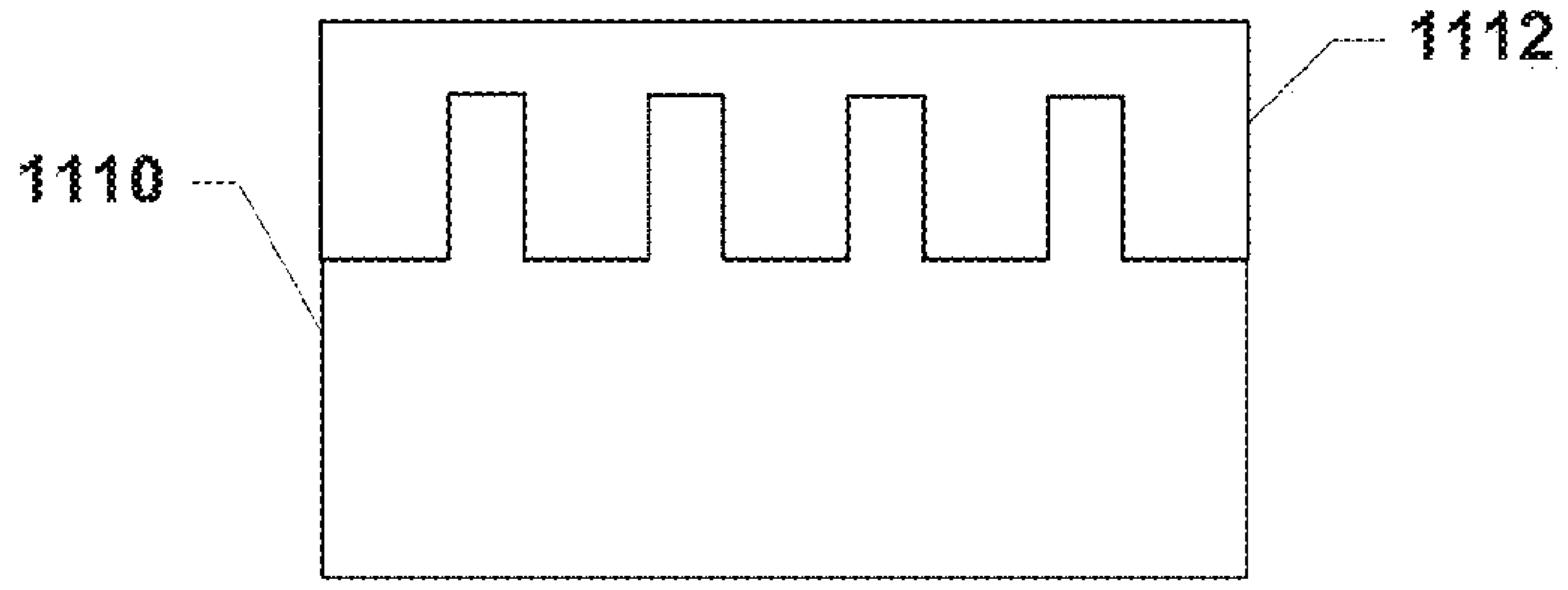

FIG. 15L

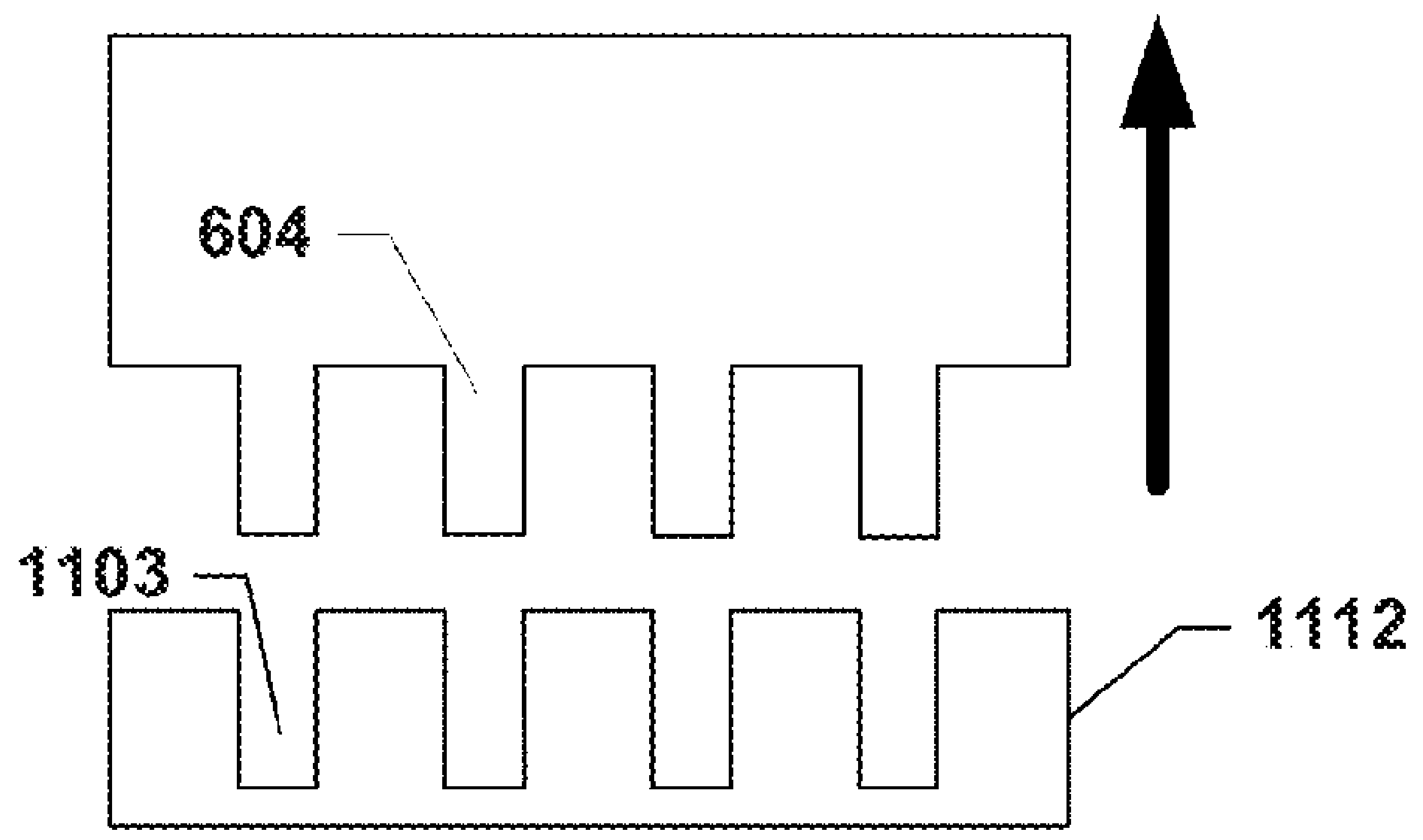

FIG. 15M

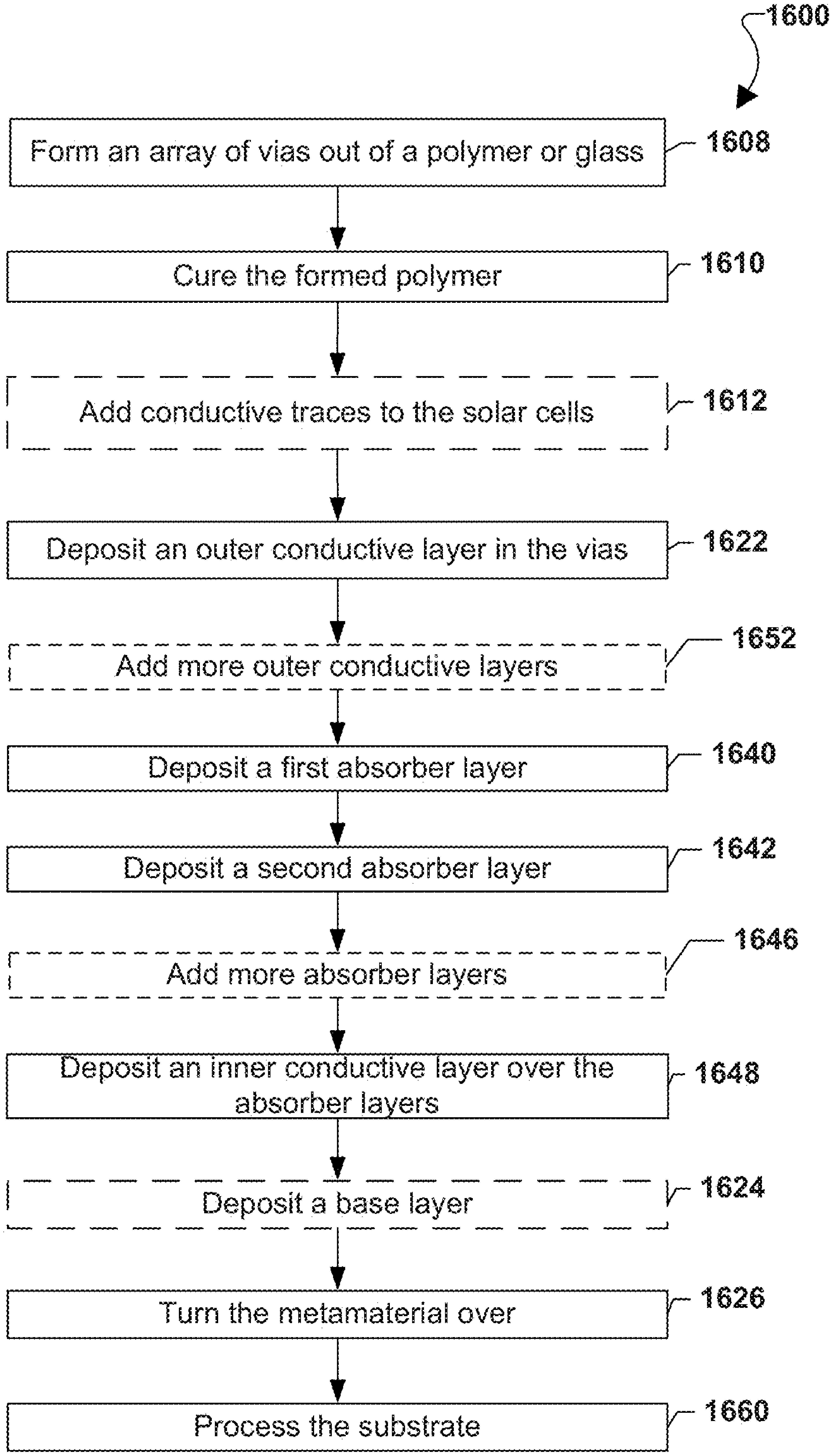
1600
Form an array of vias out of a polymer or glass
1608
Cure the formed polymer
1610
Add conductive traces to the solar cells
1612
Deposit an outer conductive layer in the vias
1622
Add more outer conductive layers
1652
Deposit a first absorber layer
1640
Deposit a second absorber layer
1642
Add more absorber layers
1646
Deposit an inner conductive layer over the absorber layers
1648
Deposit a base layer
1624
Turn the metamaterial over
1626
Process the substrate
1660

FIG. 16

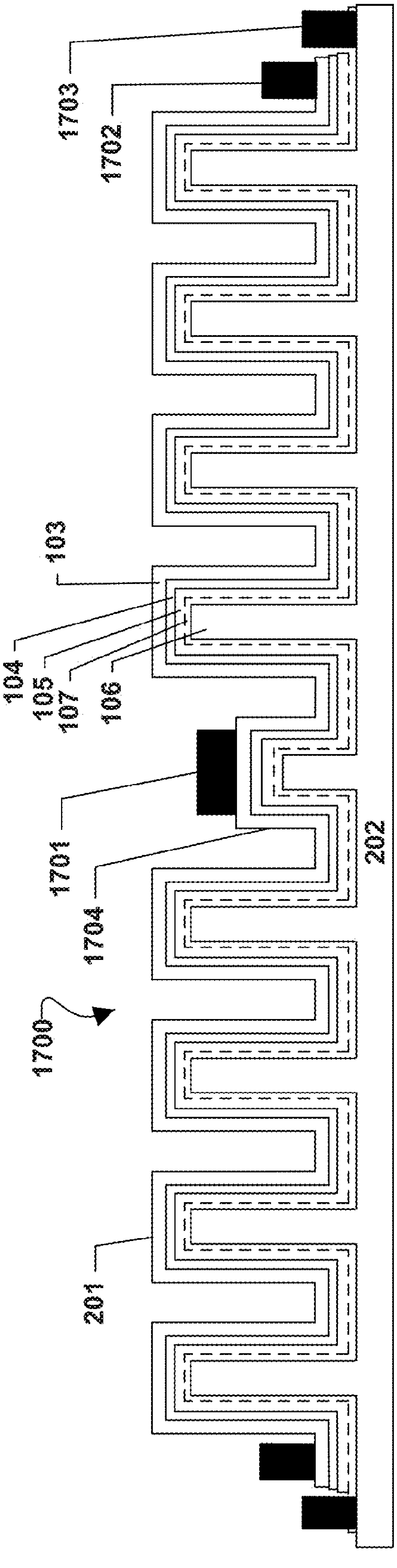

FIG. 17

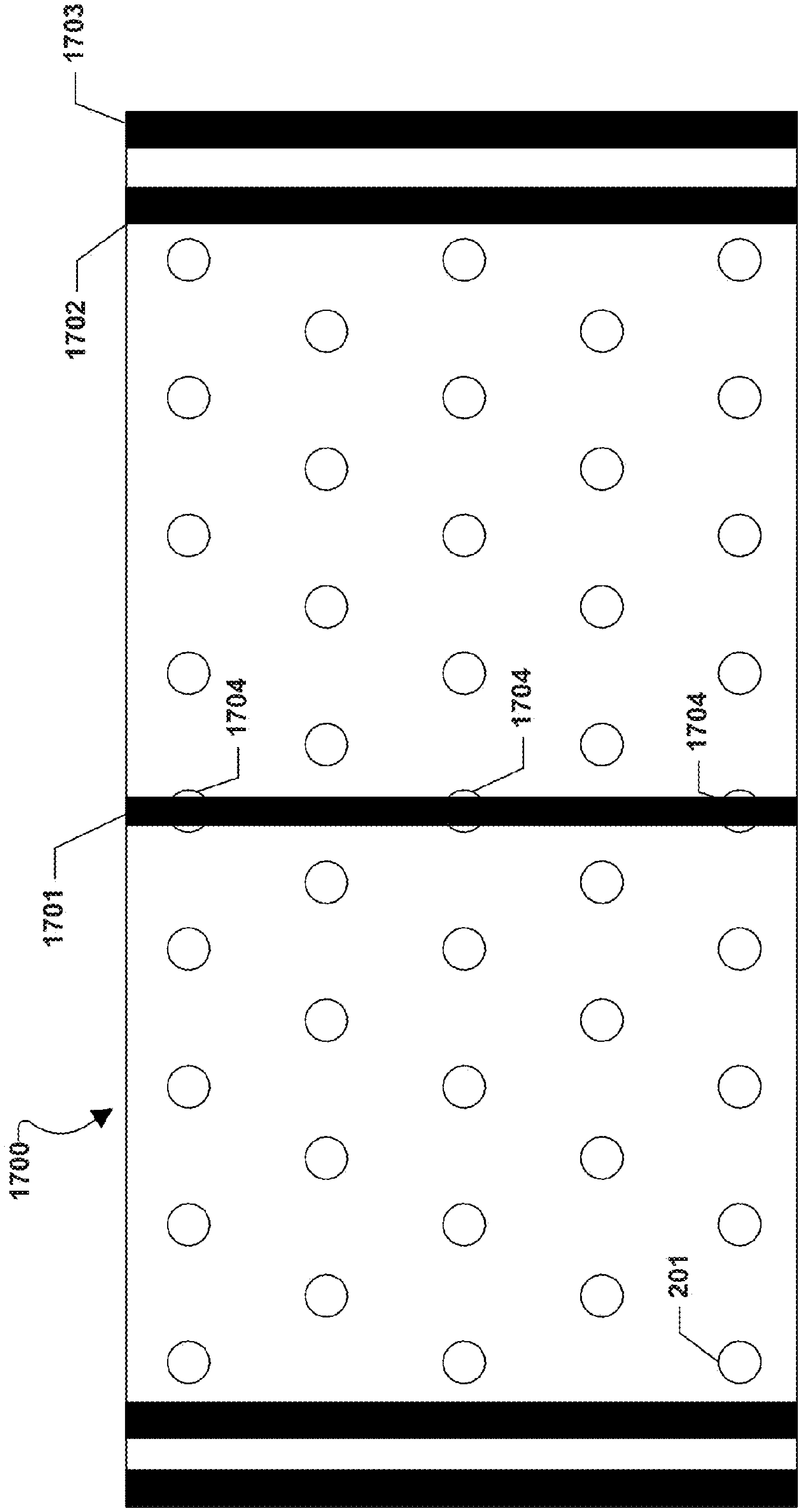

FIG. 18

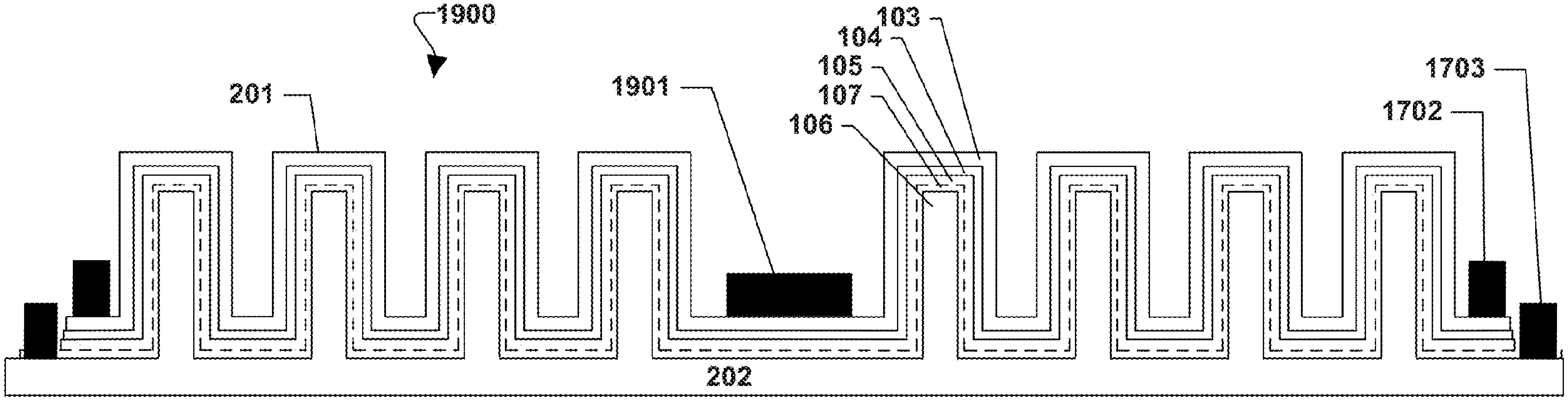

FIG. 19

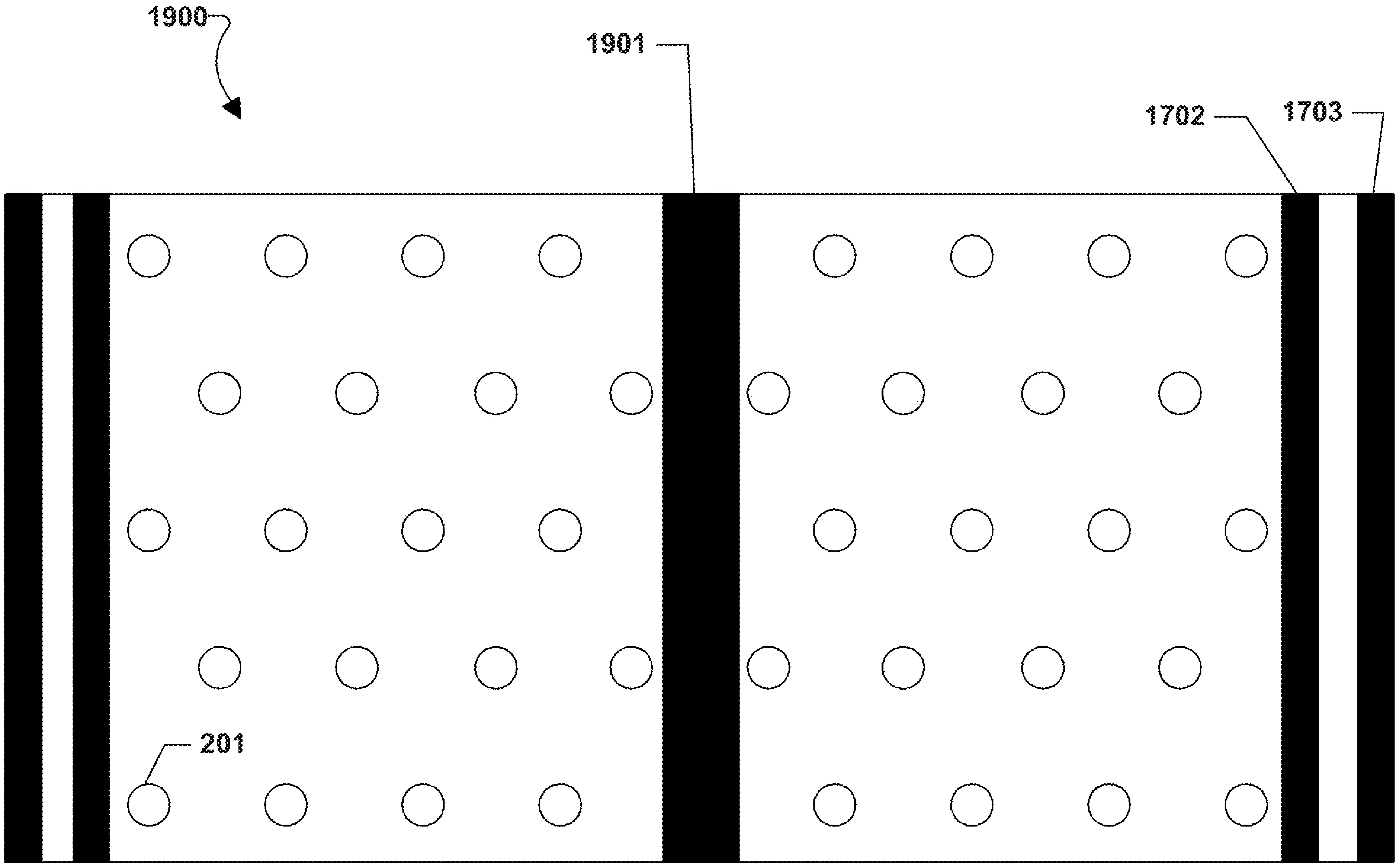

FIG. 20

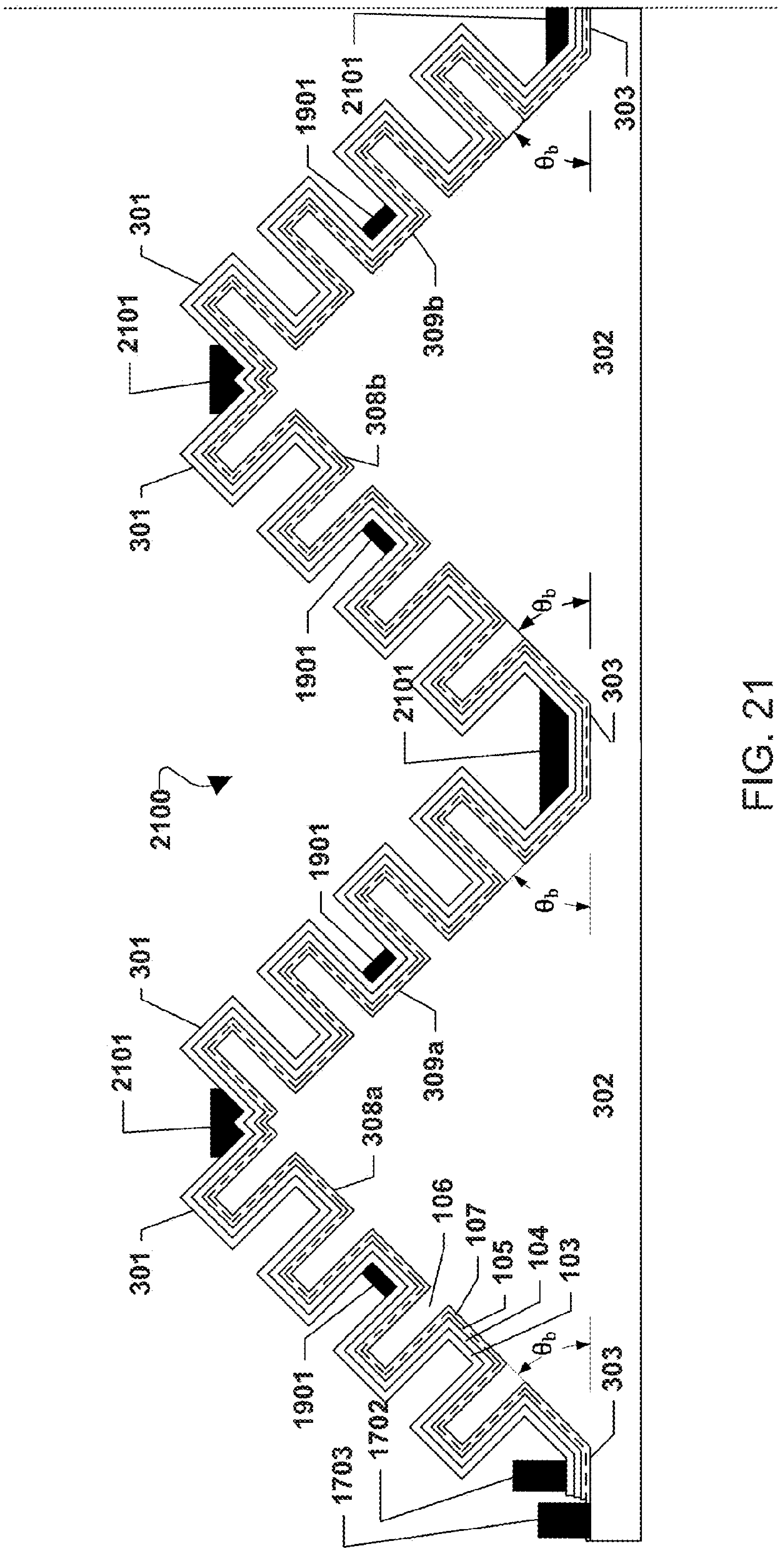
2100
301
301
301
301
2101
2101
2101
2101
1901
1901
1901
1901
308a
308b
309a
309b
302
302
303
303
303
θb
θb
θb
θb
106
107
105
104
103
1702
1703

FIG. 21

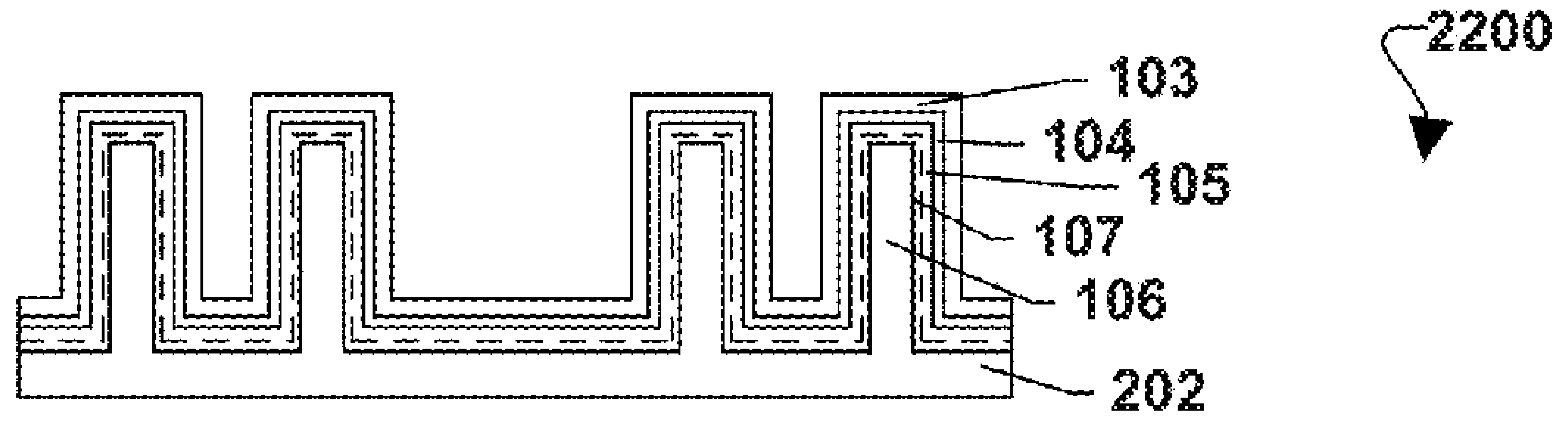

FIG. 22A

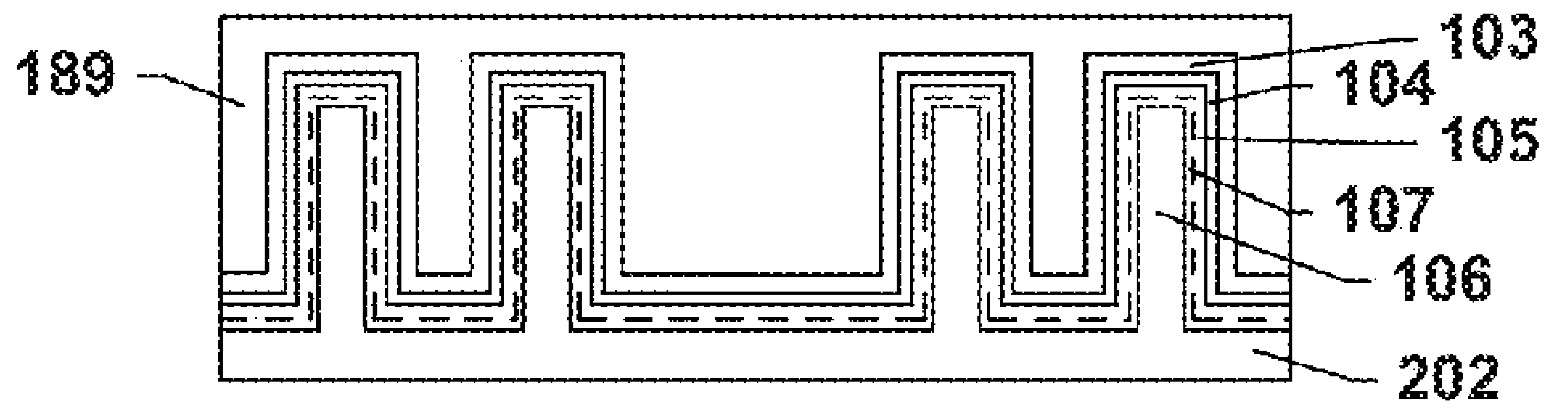

FIG. 22B

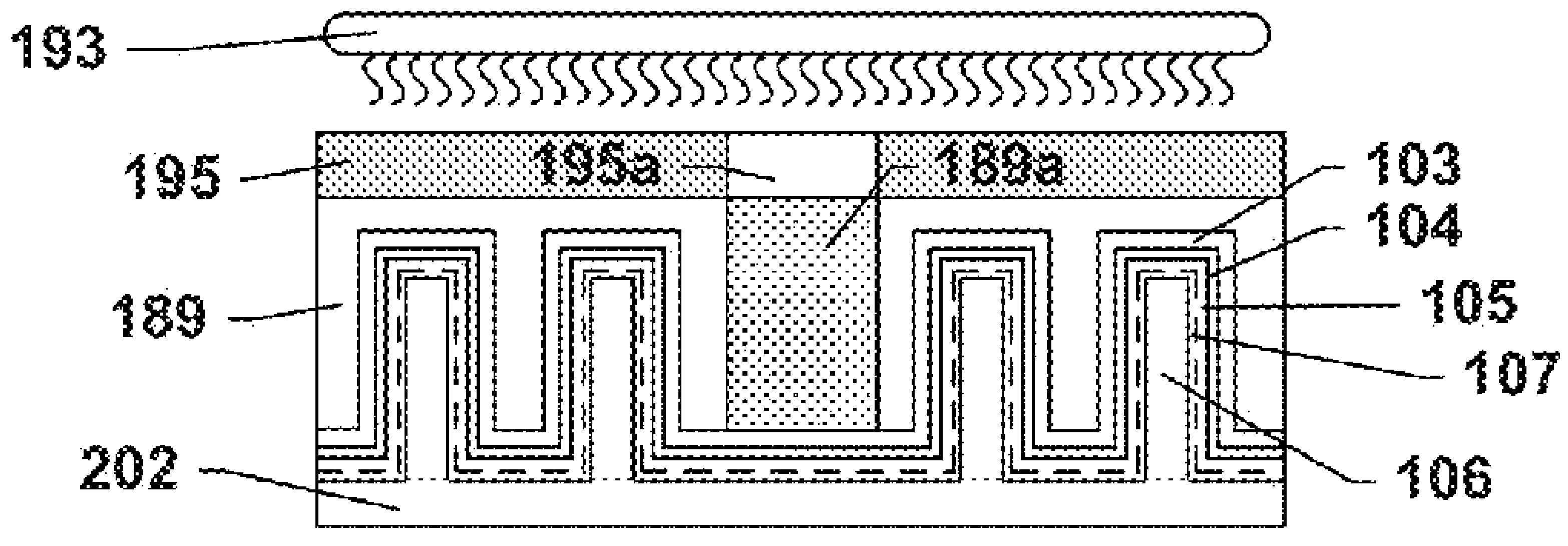

FIG. 22C

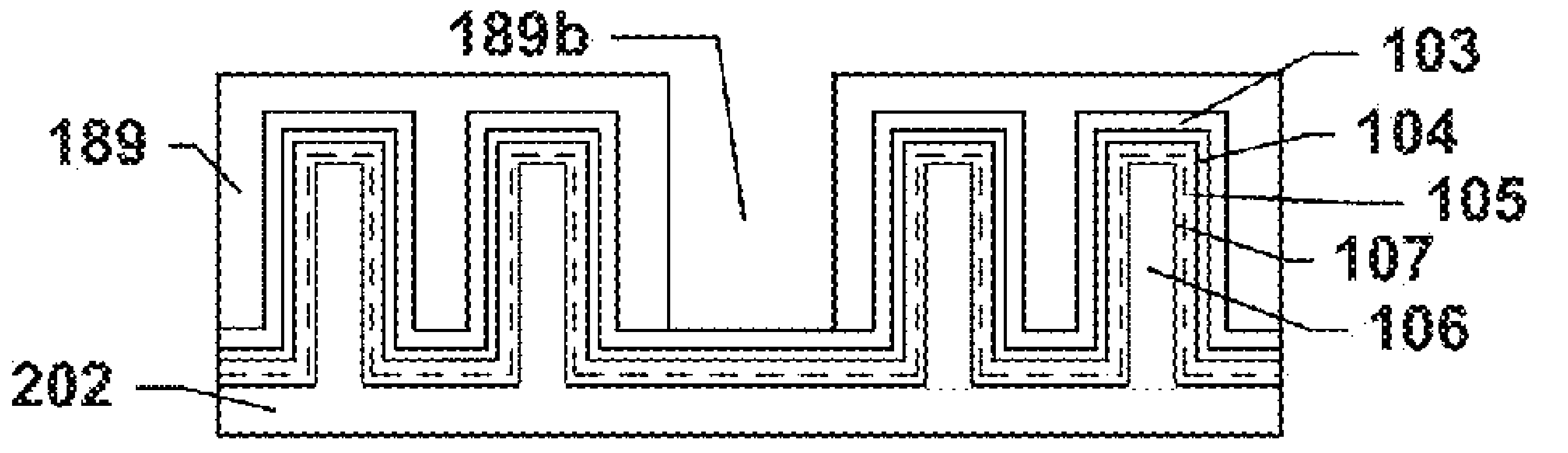

FIG. 22D

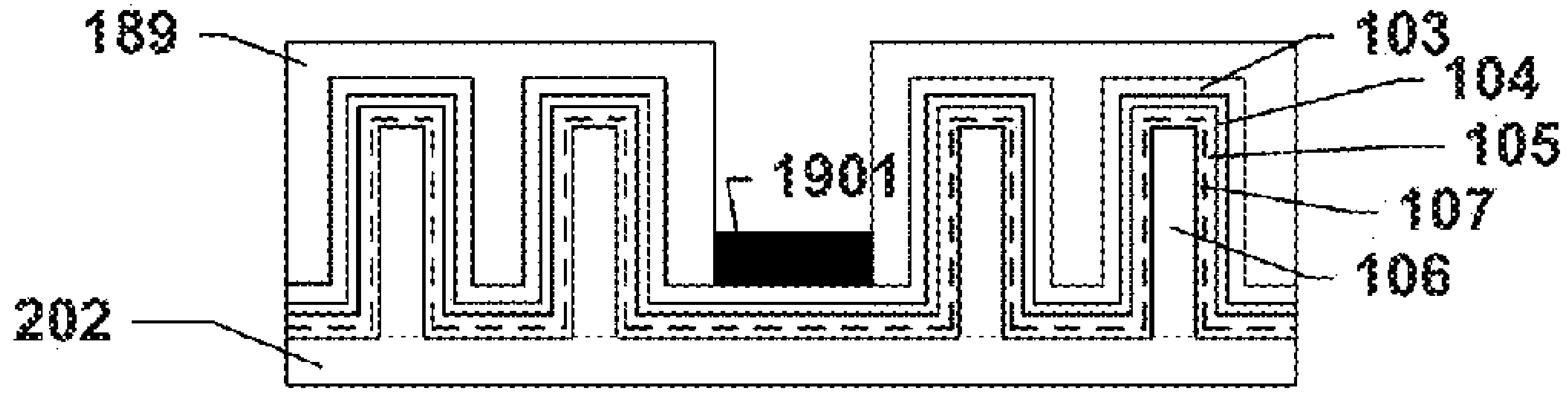

FIG. 22E

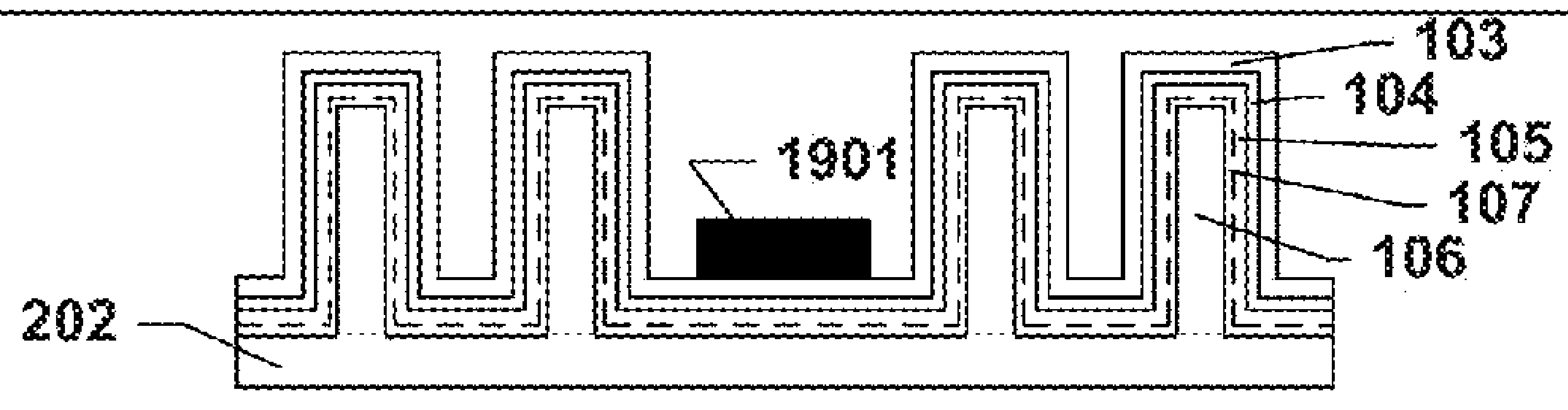

FIG. 22F

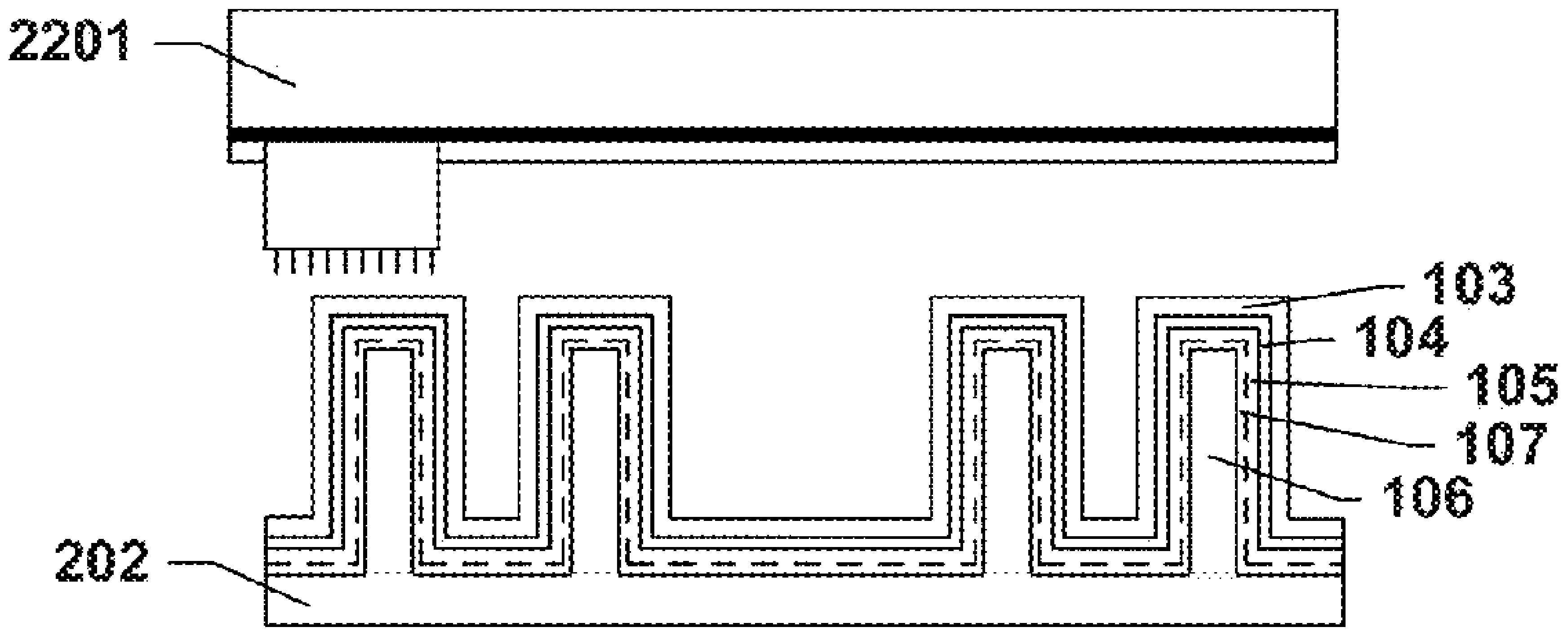

FIG. 22G

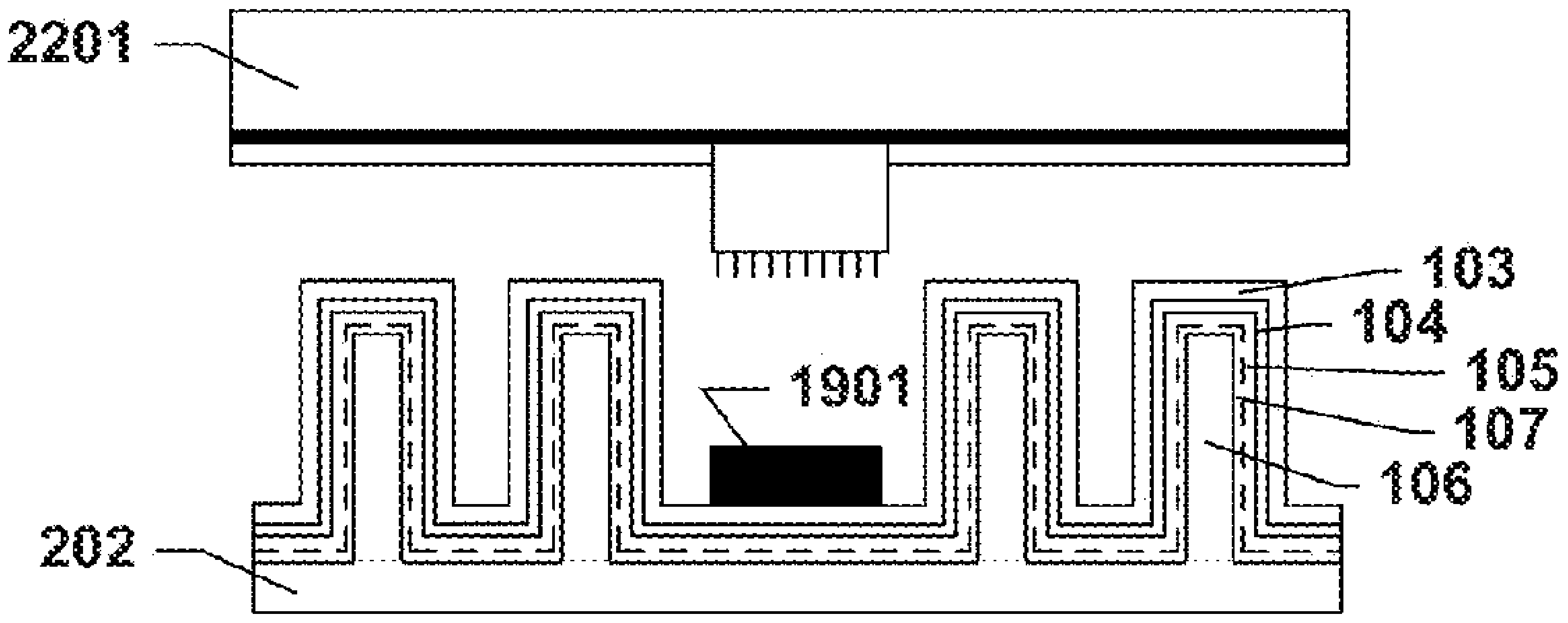

FIG. 22H

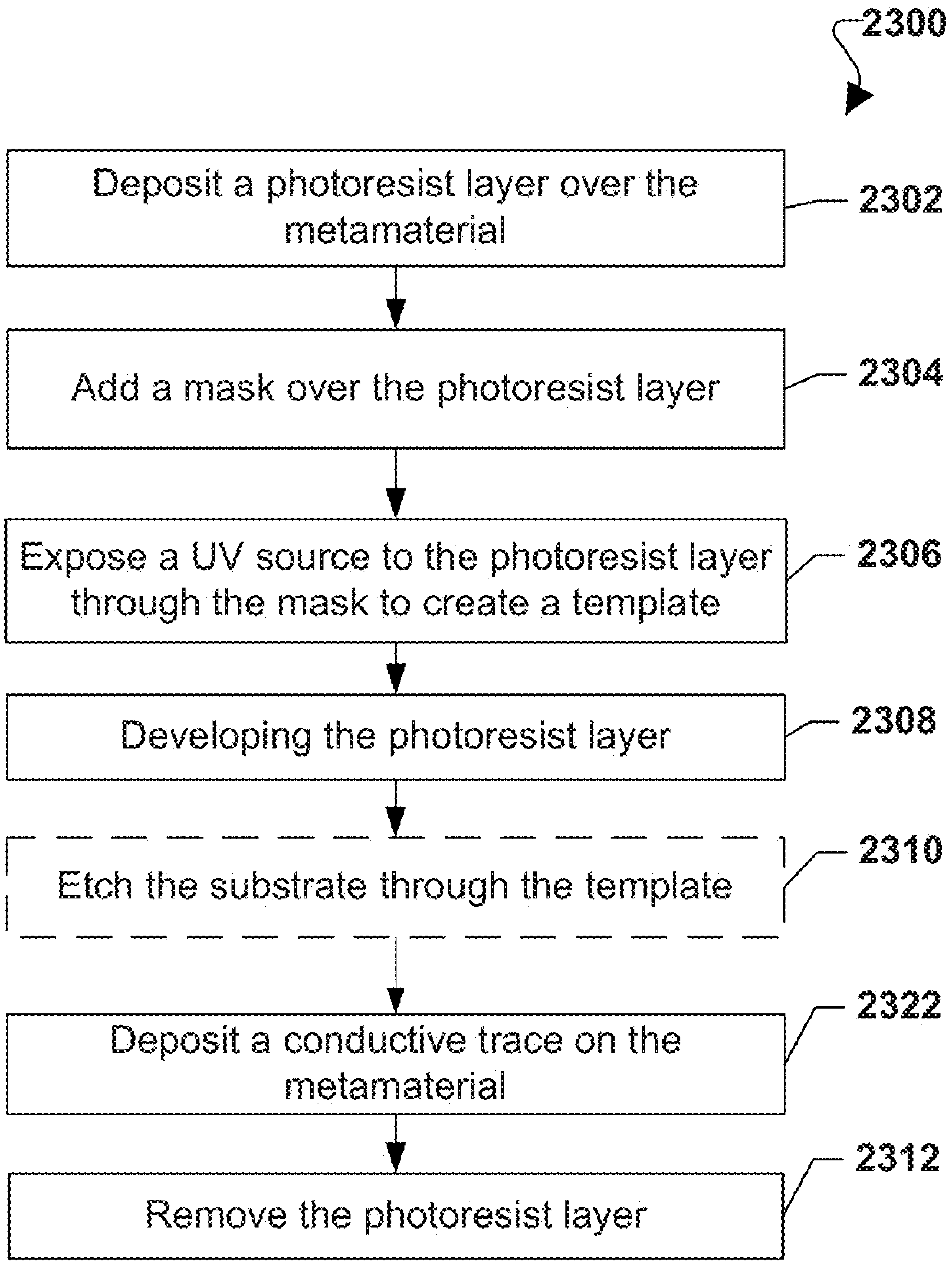
2300
Deposit a photoresist layer over the metamaterial
2302
Add a mask over the photoresist layer
2304
Expose a UV source to the photoresist layer through the mask to create a template
2306
Developing the photoresist layer
2308
Etch the substrate through the template
2310
Deposit a conductive trace on the metamaterial
2322
Remove the photoresist layer
2312

FIG. 23

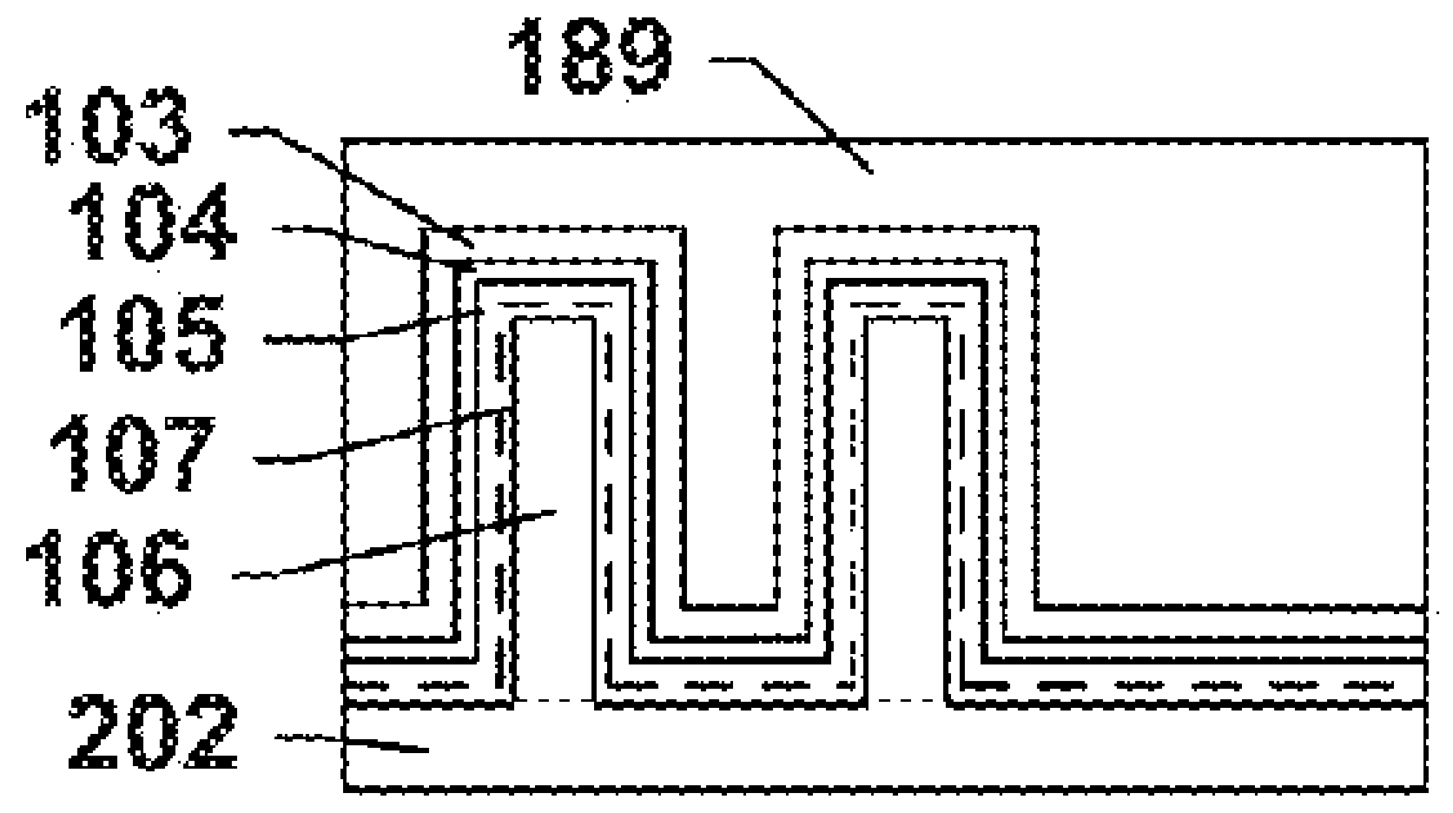

FIG. 24A

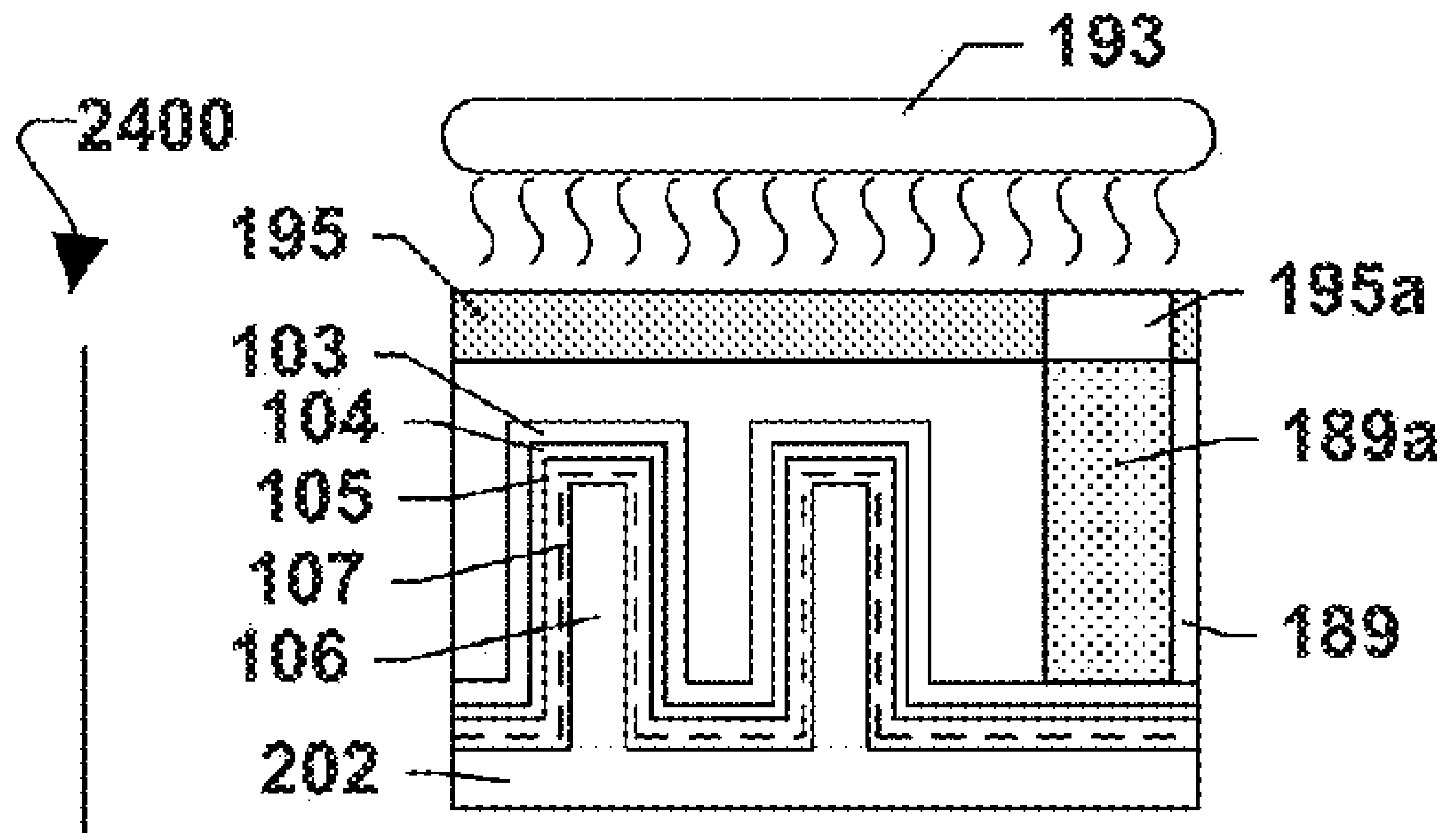

FIG. 24B

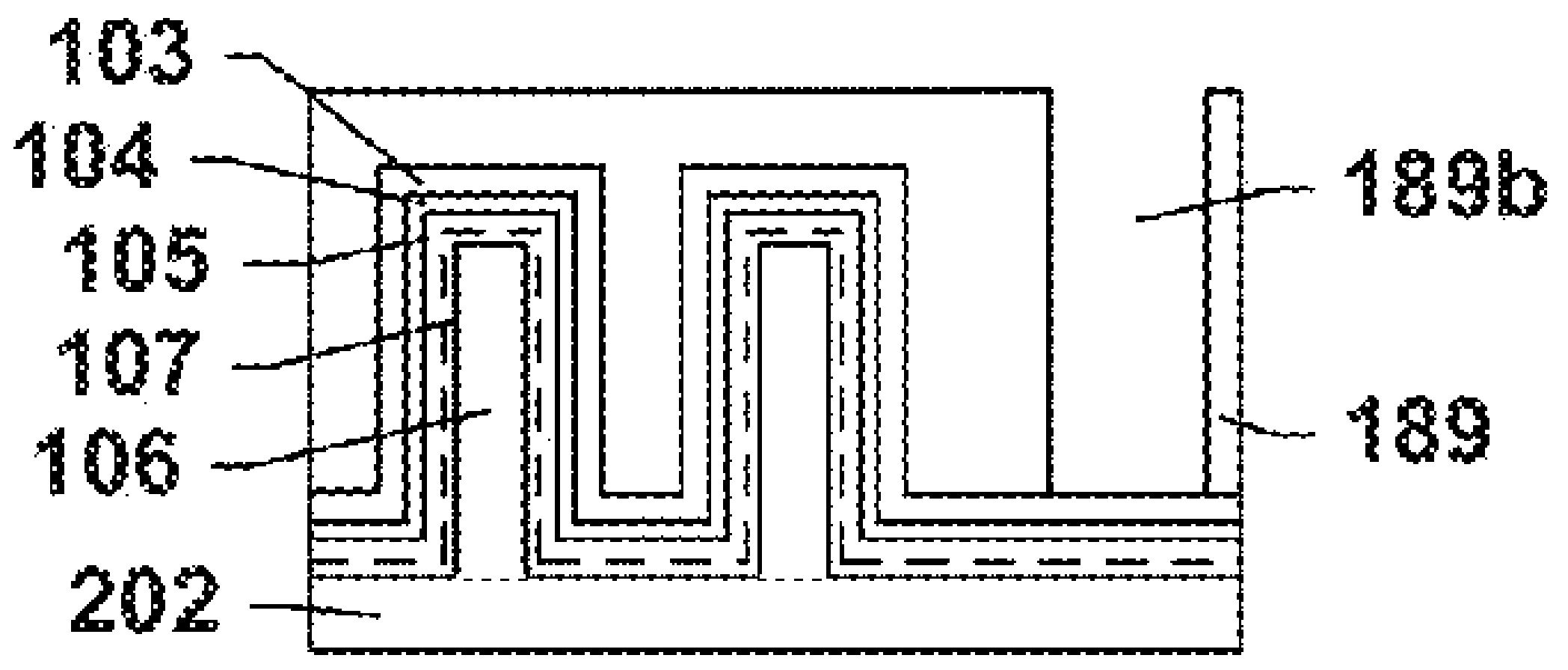

FIG. 24C

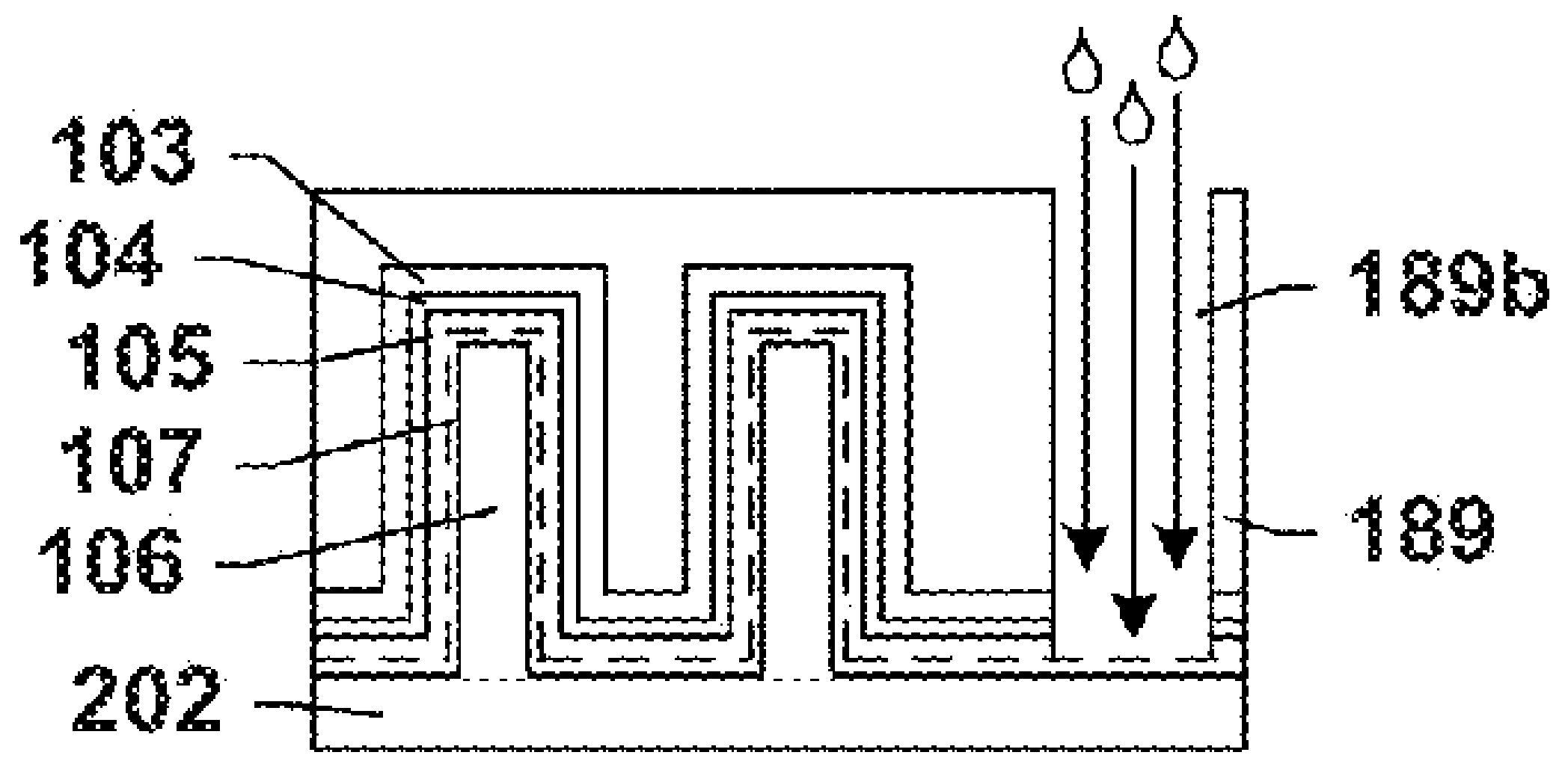

FIG. 24D

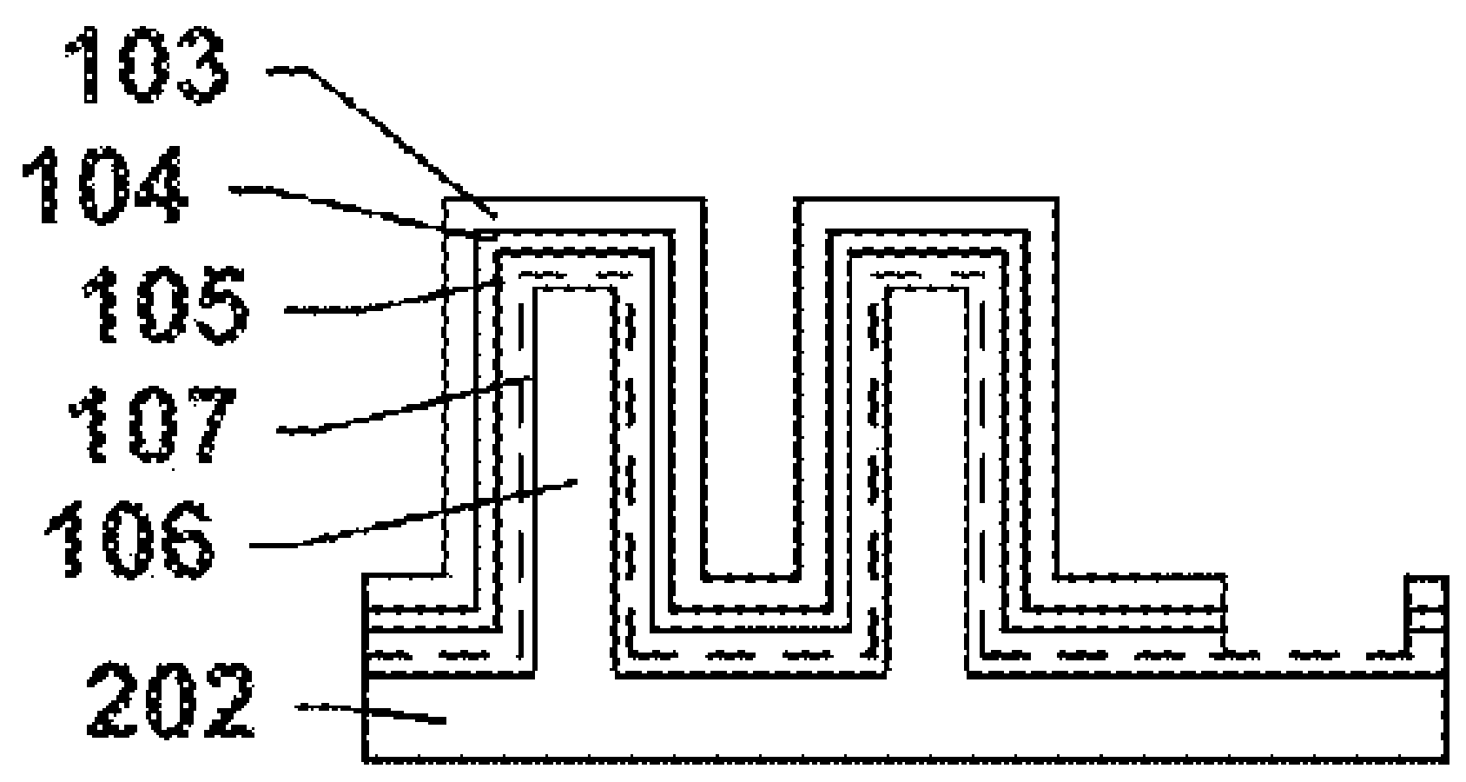

FIG. 24E

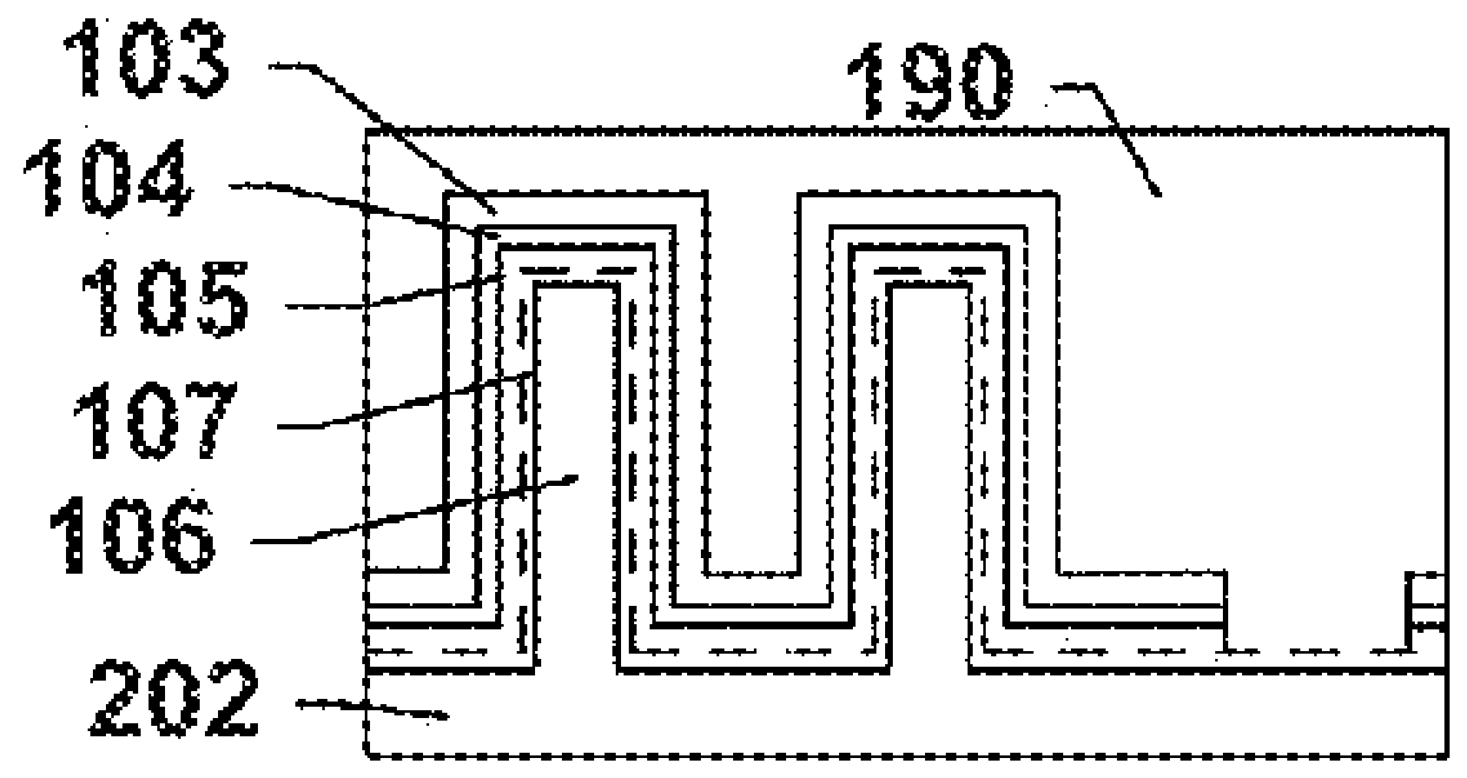

FIG. 24F

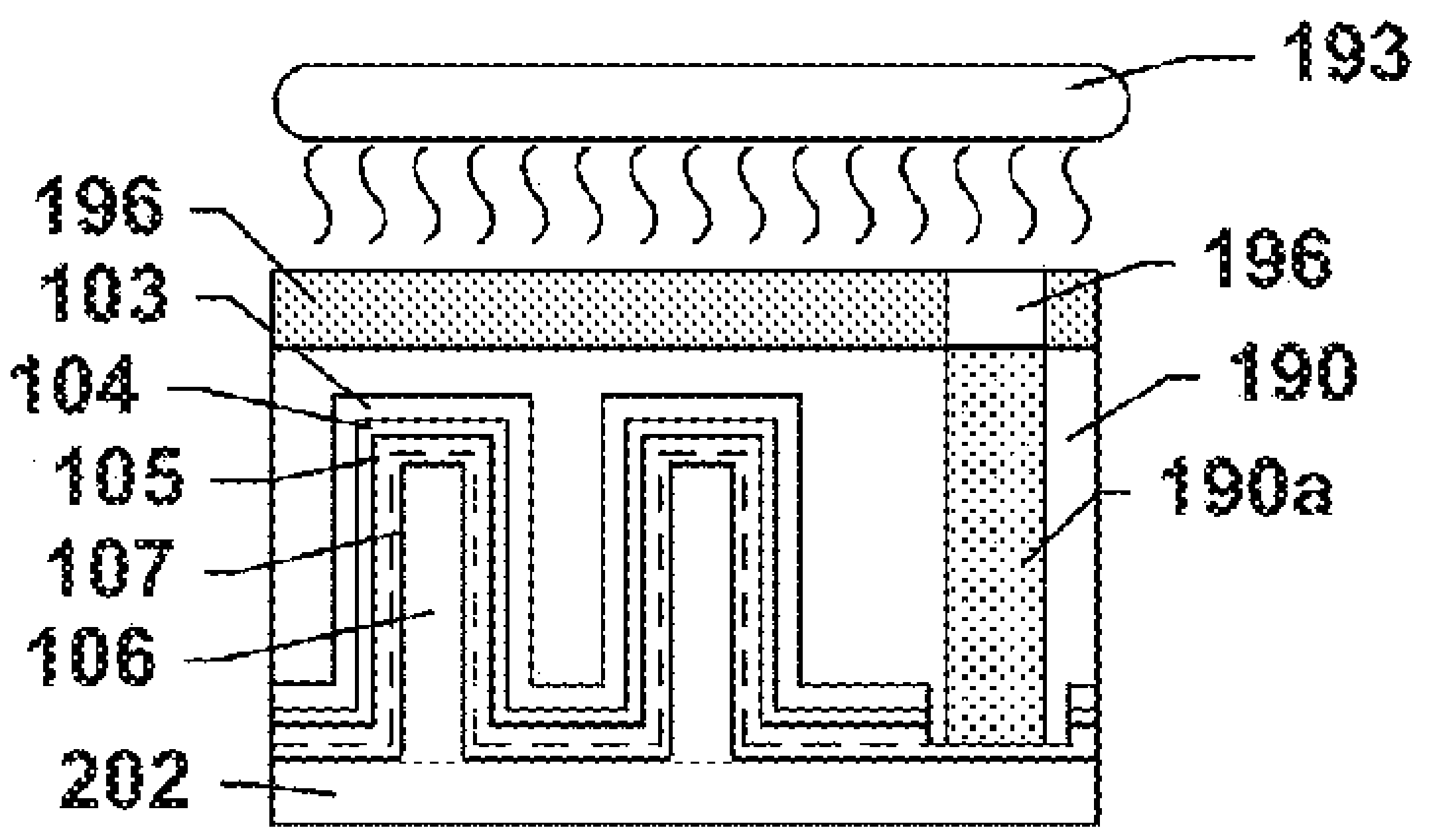

FIG. 24G

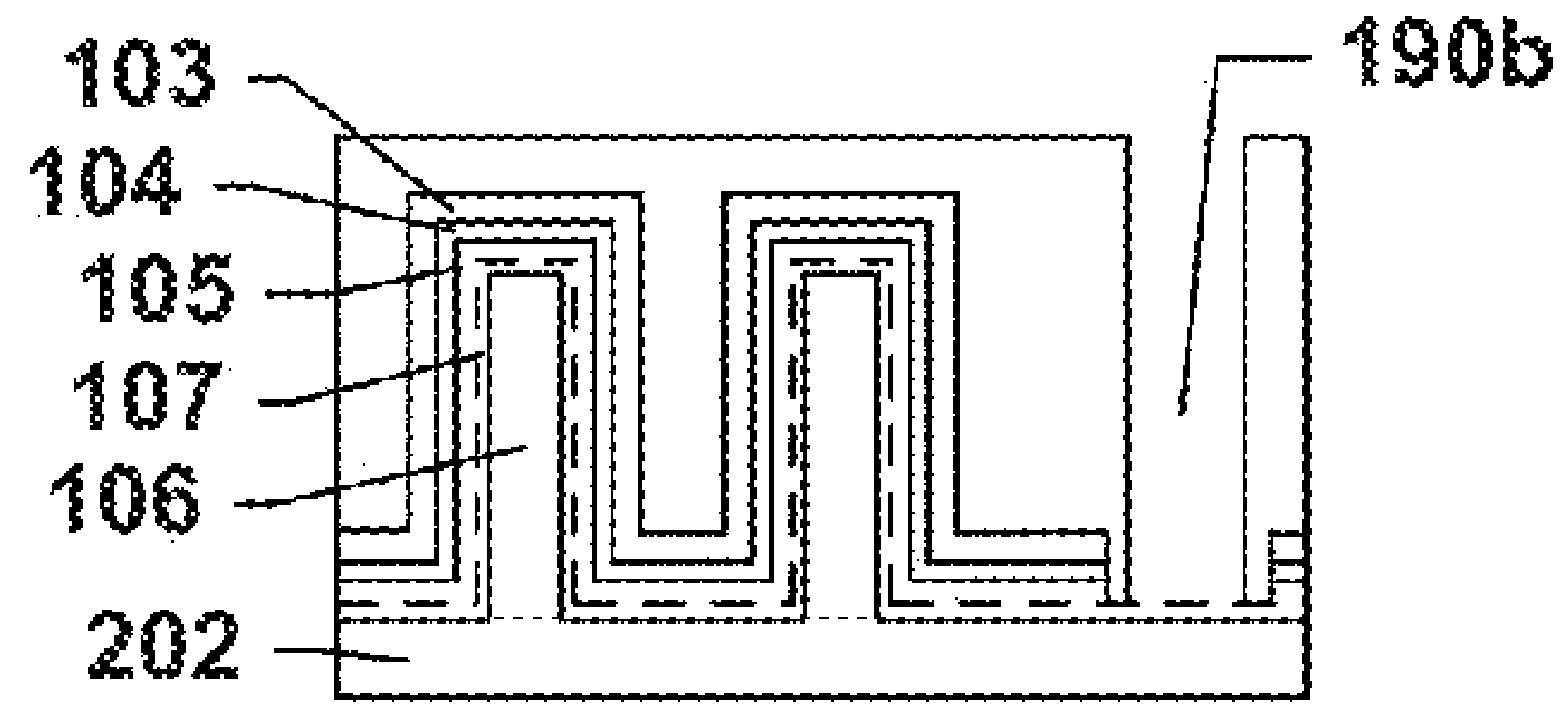

FIG. 24H

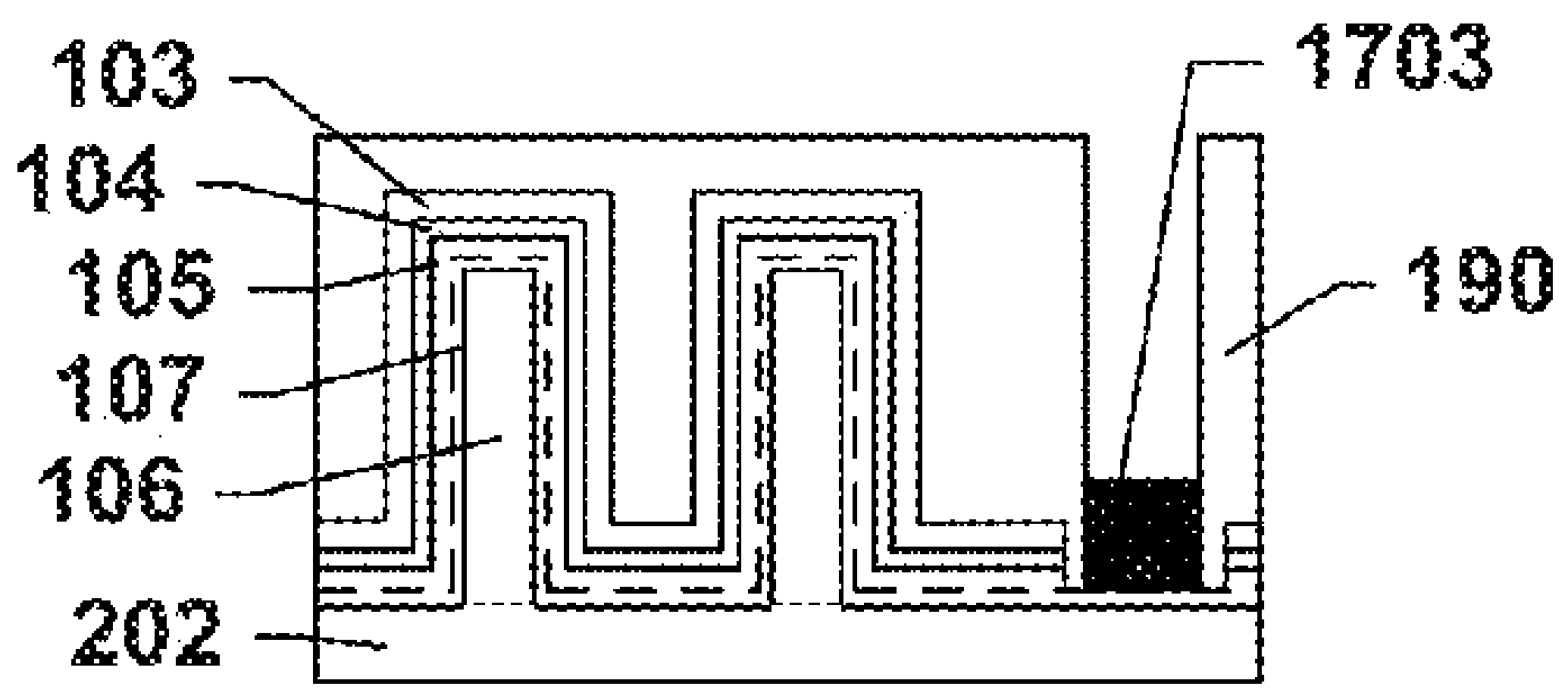

FIG. 24I

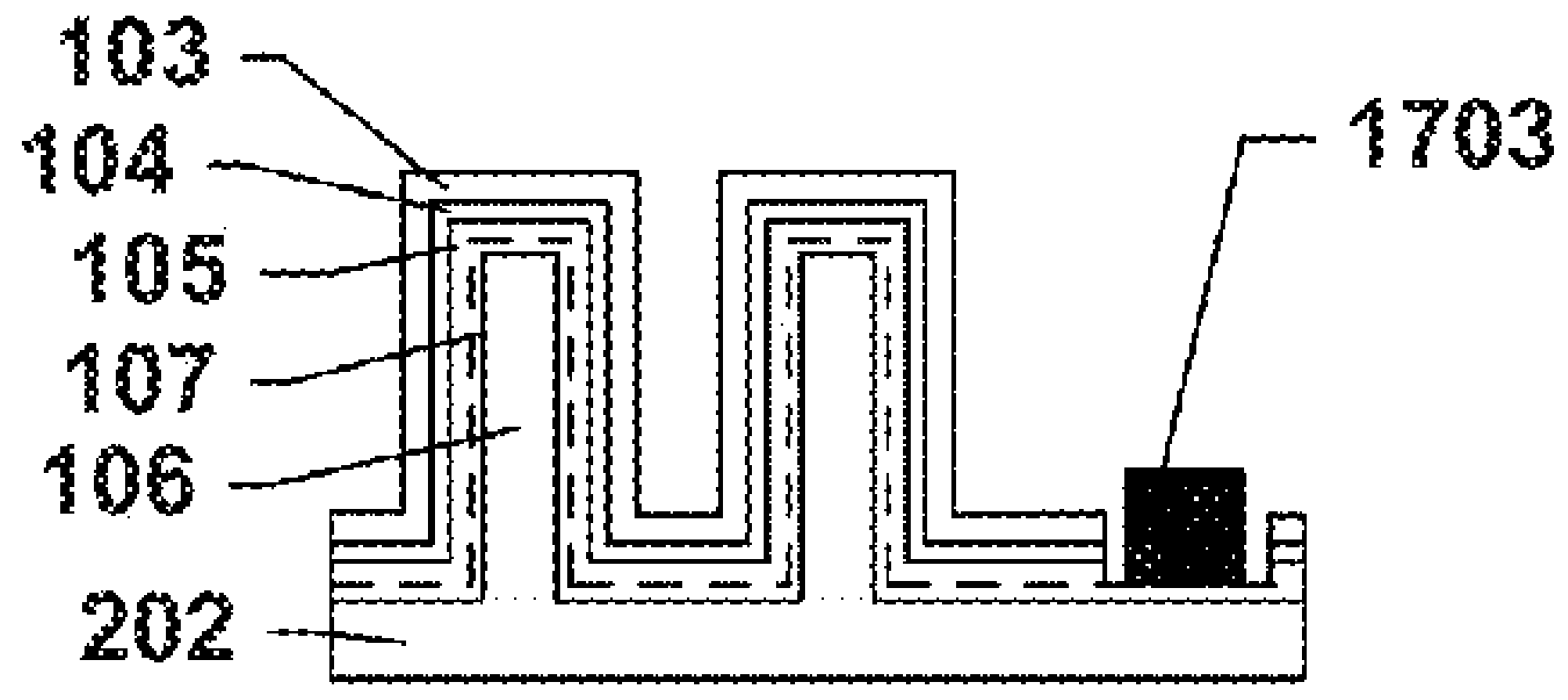

FIG. 24J

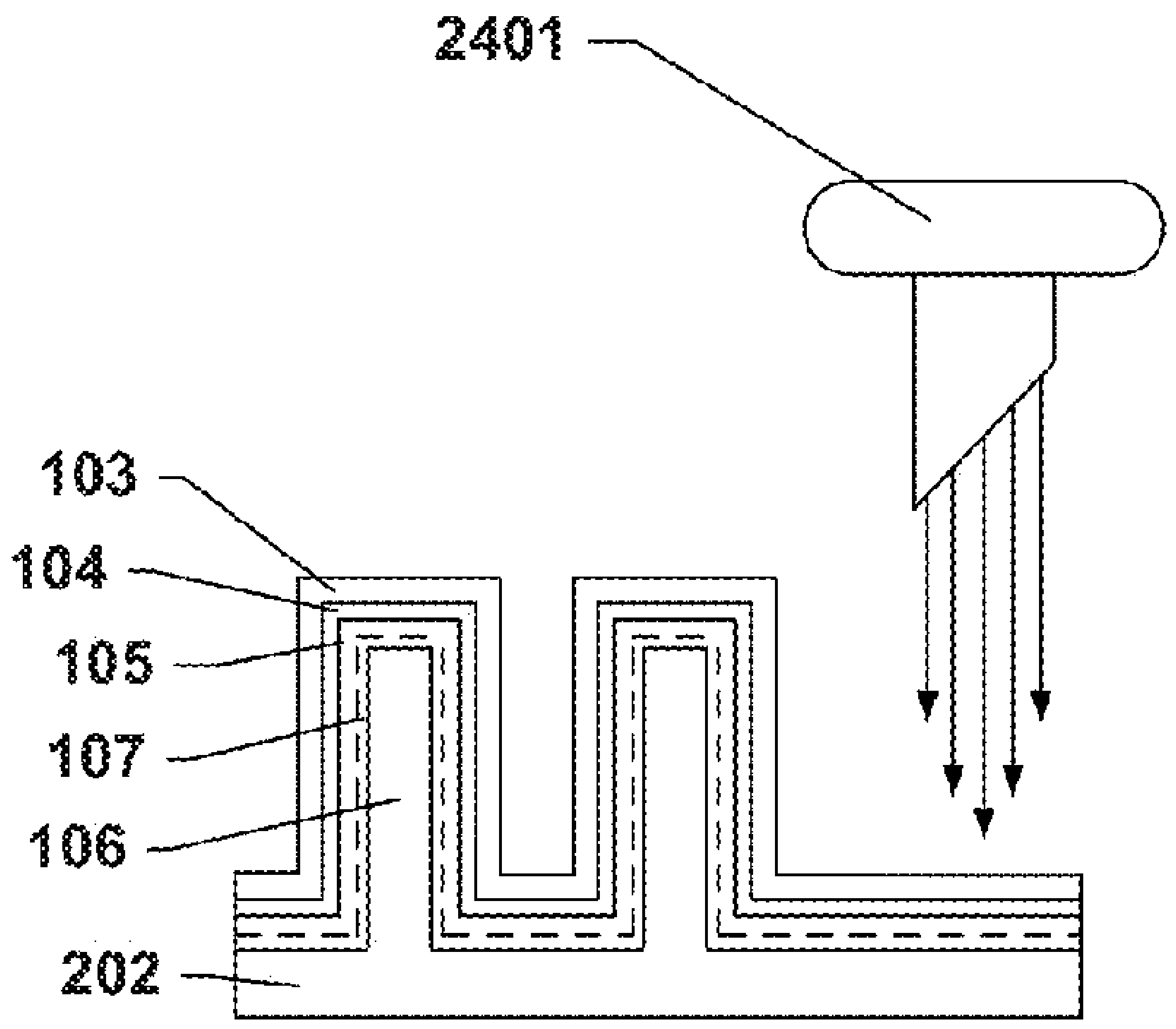

FIG. 24K

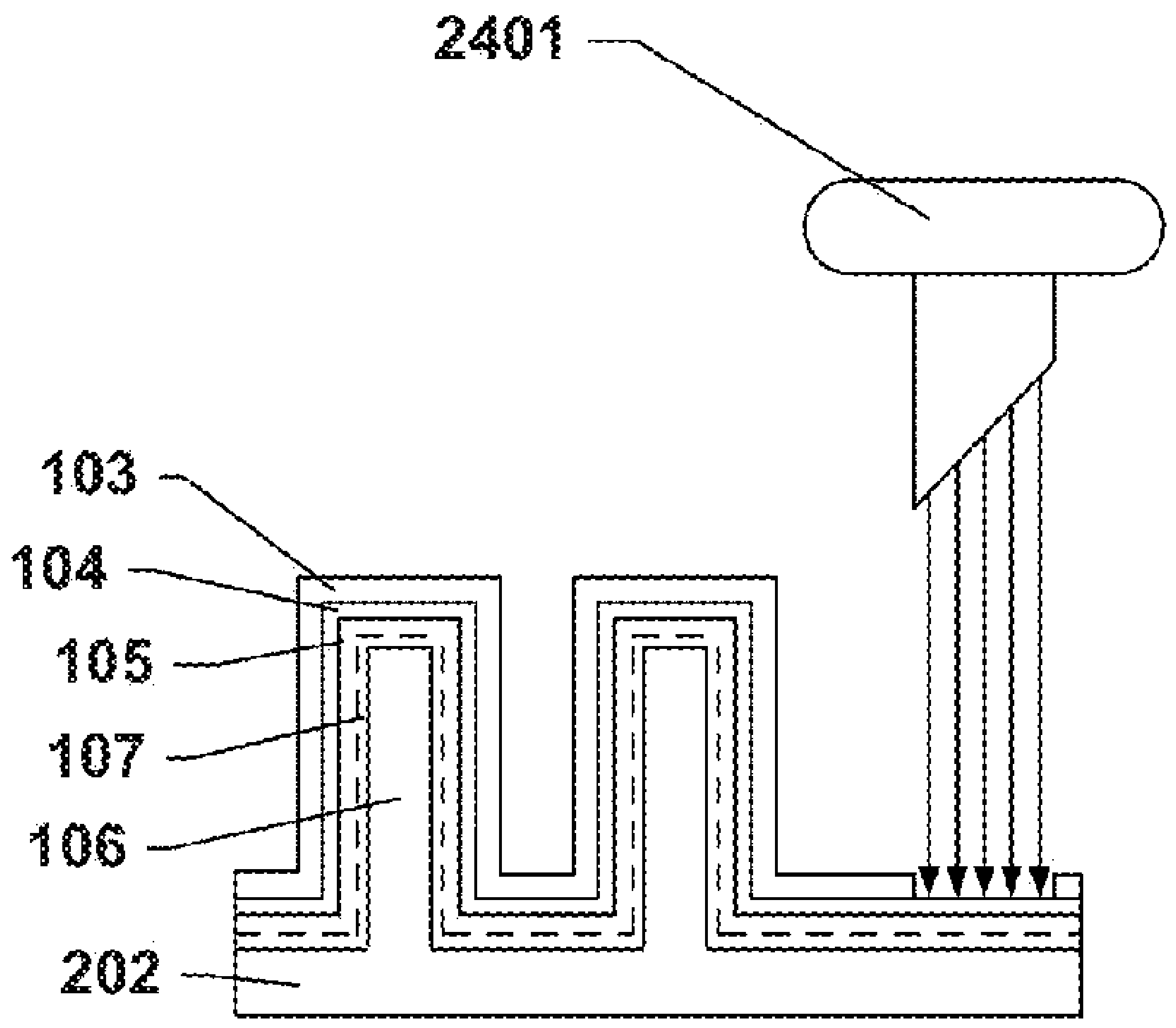

FIG. 24L

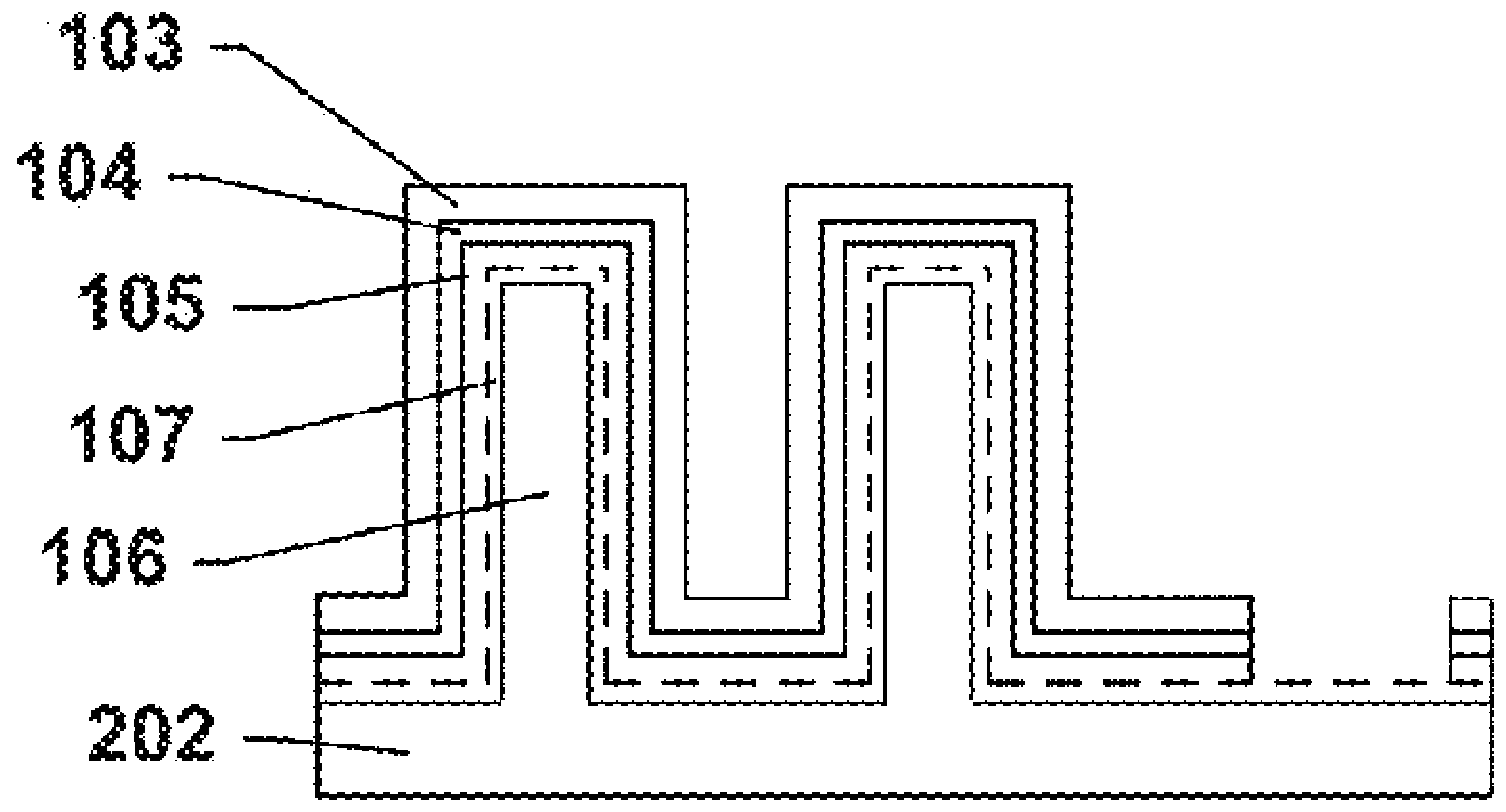

FIG. 24M

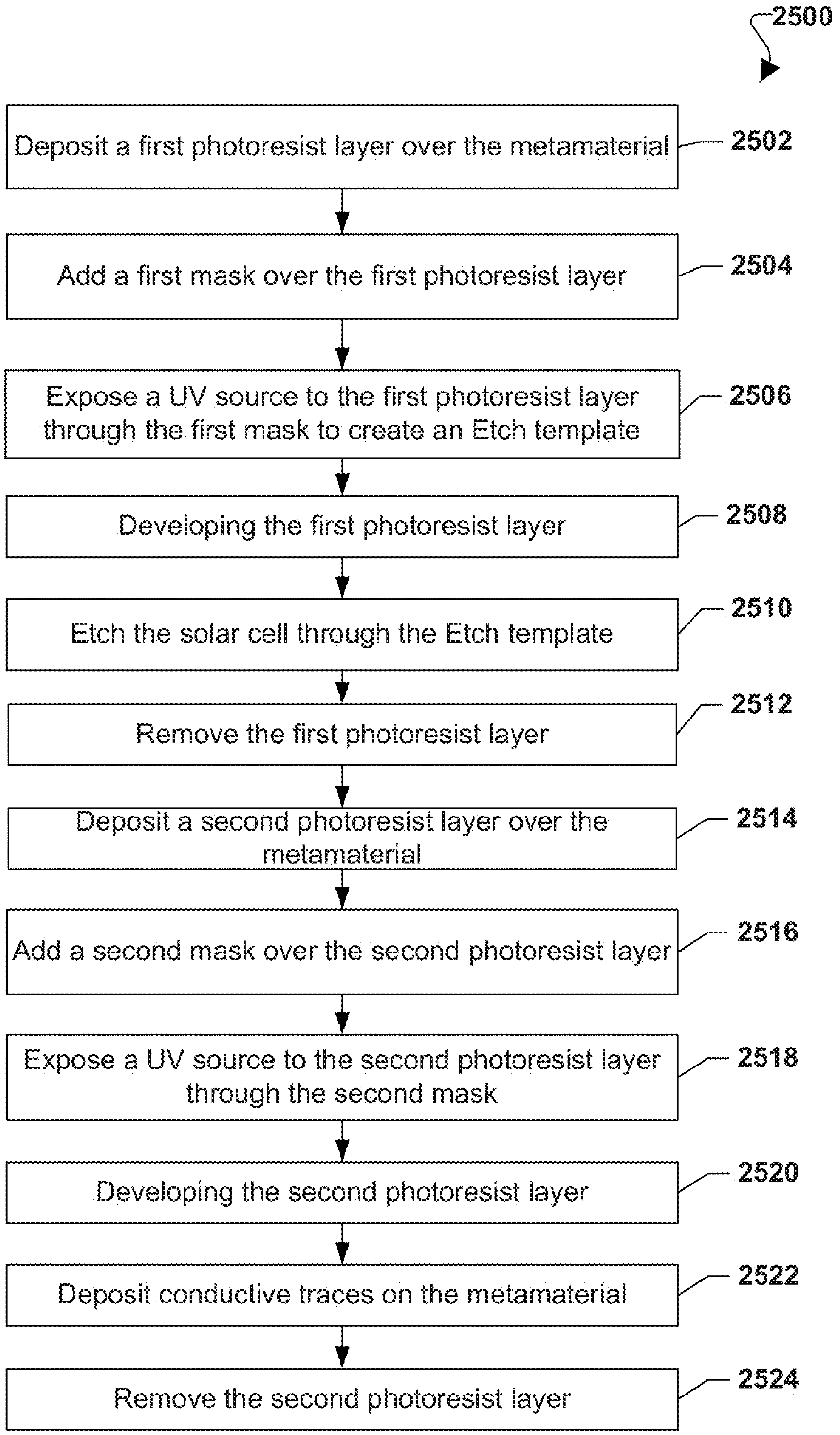
2500
Deposit a first photoresist layer over the metamaterial
2502
Add a first mask over the first photoresist layer
2504
Expose a UV source to the first photoresist layer through the first mask to create an Etch template
2506
Developing the first photoresist layer
2508
Etch the solar cell through the Etch template
2510
Remove the first photoresist layer
2512
Deposit a second photoresist layer over the metamaterial
2514
Add a second mask over the second photoresist layer
2516
Expose a UV source to the second photoresist layer through the second mask
2518
Developing the second photoresist layer
2520
Deposit conductive traces on the metamaterial
2522
Remove the second photoresist layer
2524

FIG. 25

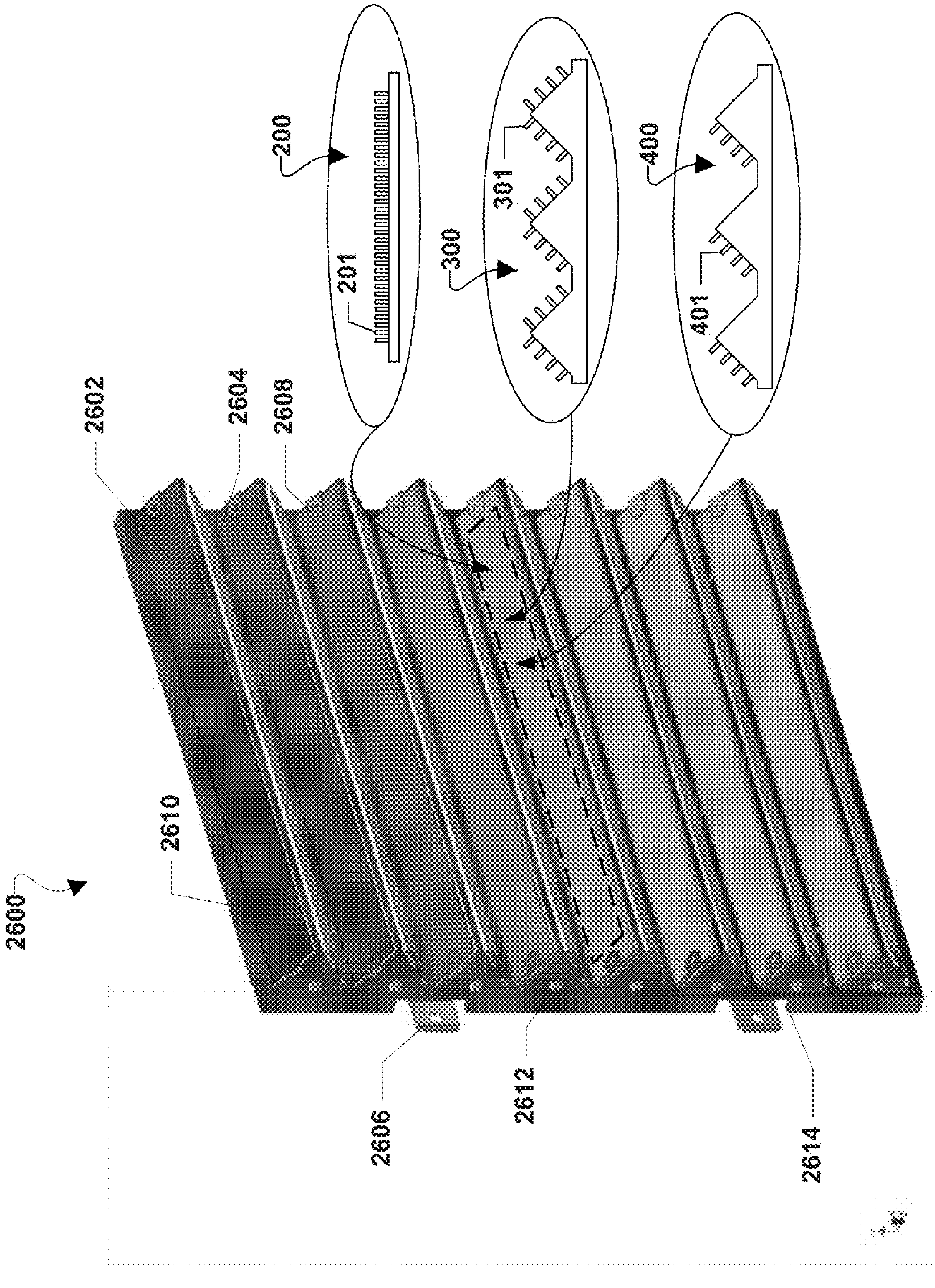
2600
2610
2602
2604
2608
200
201
300
301
400
401
2606
2612
2614

FIG. 26

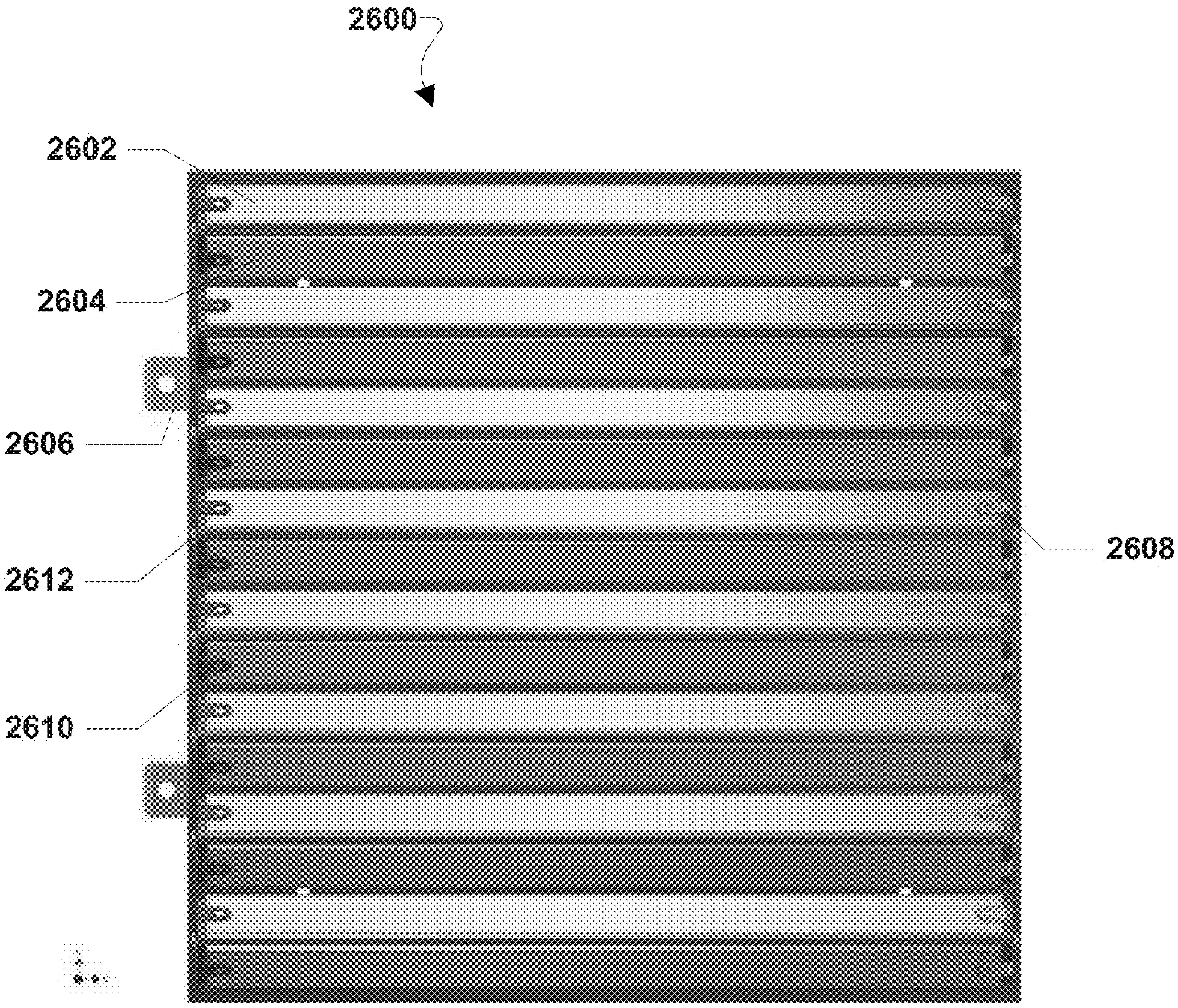

FIG. 27

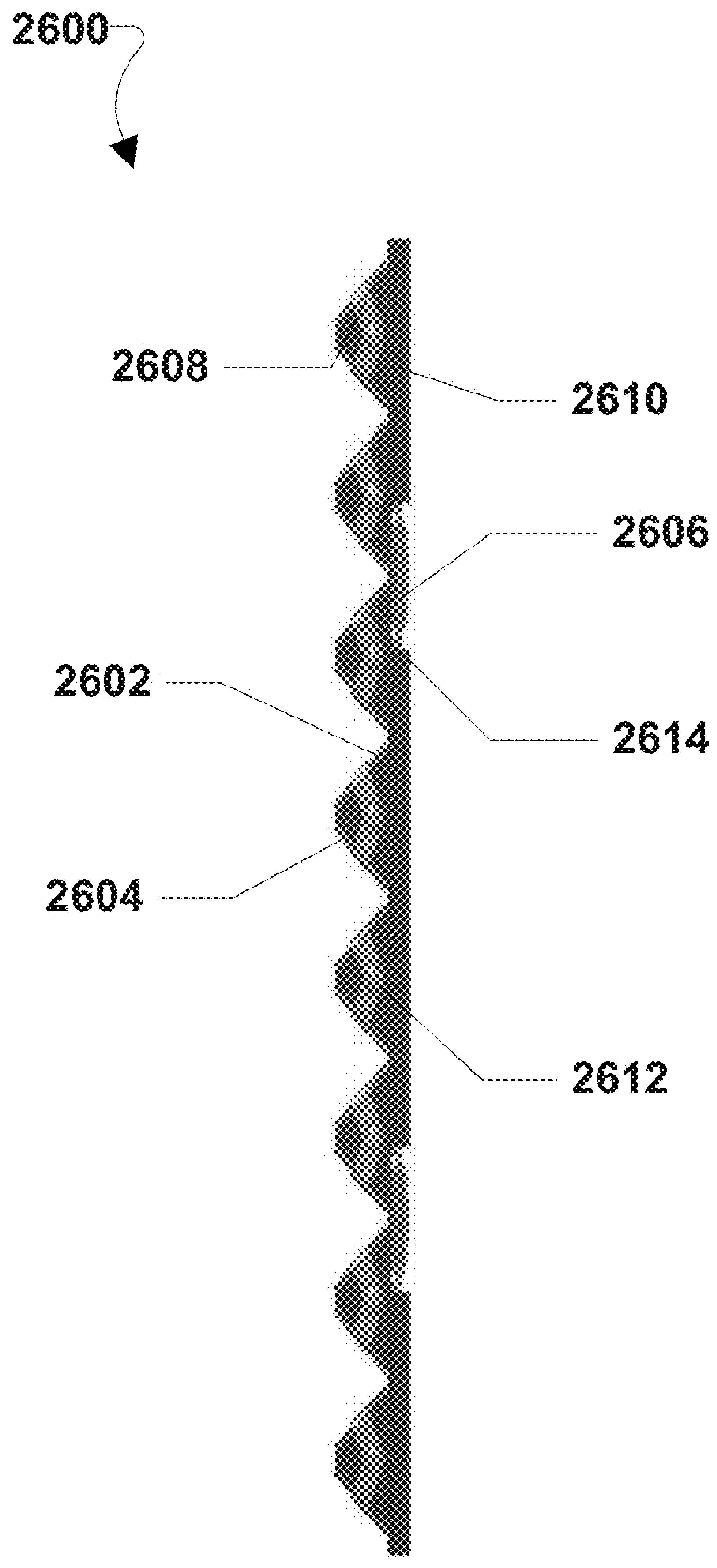

FIG. 28

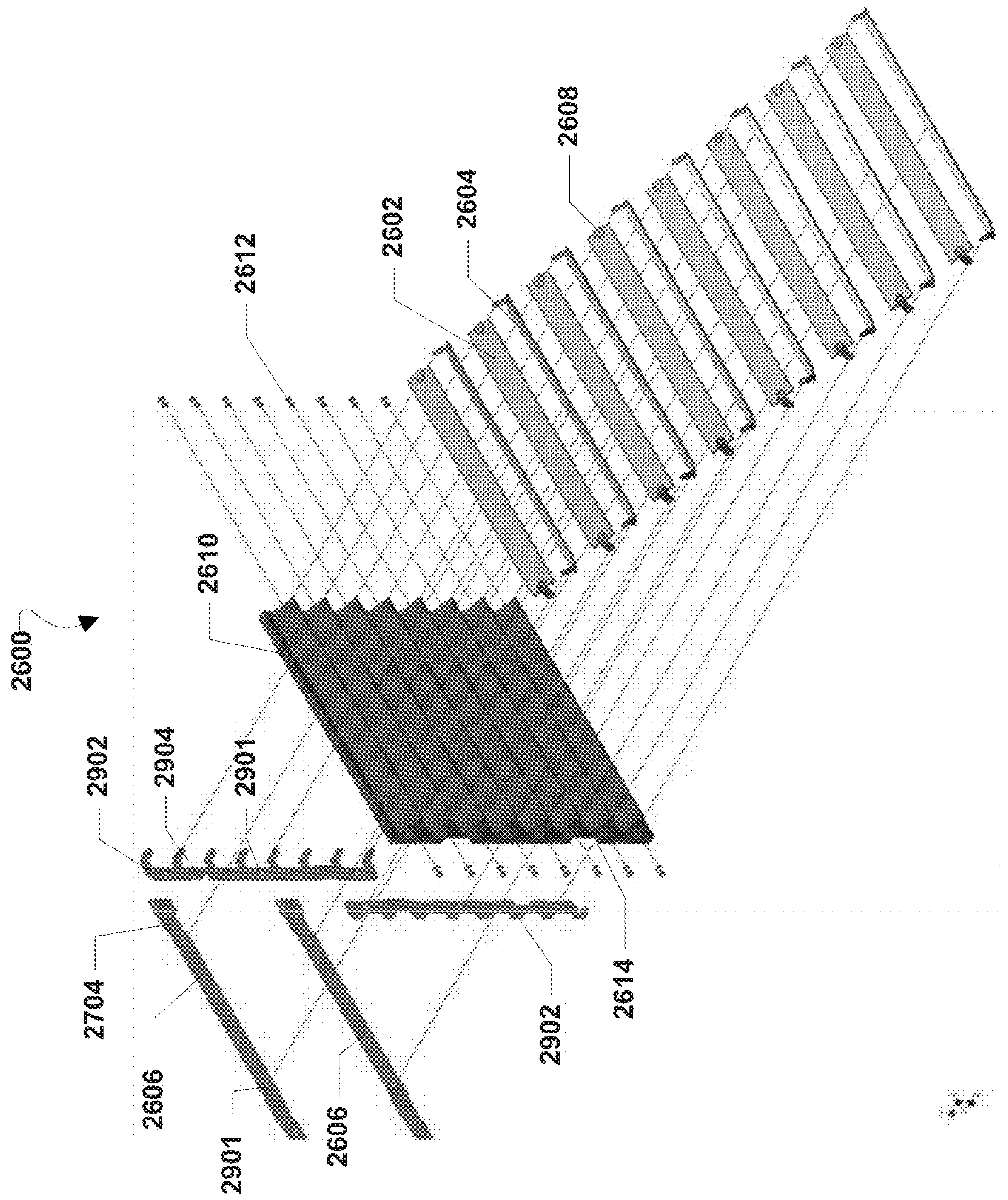
2600
2902
2904
2901
2610
2612
2602
2604
2608
2704
2606
2901
2606
2902
2614

FIG. 29

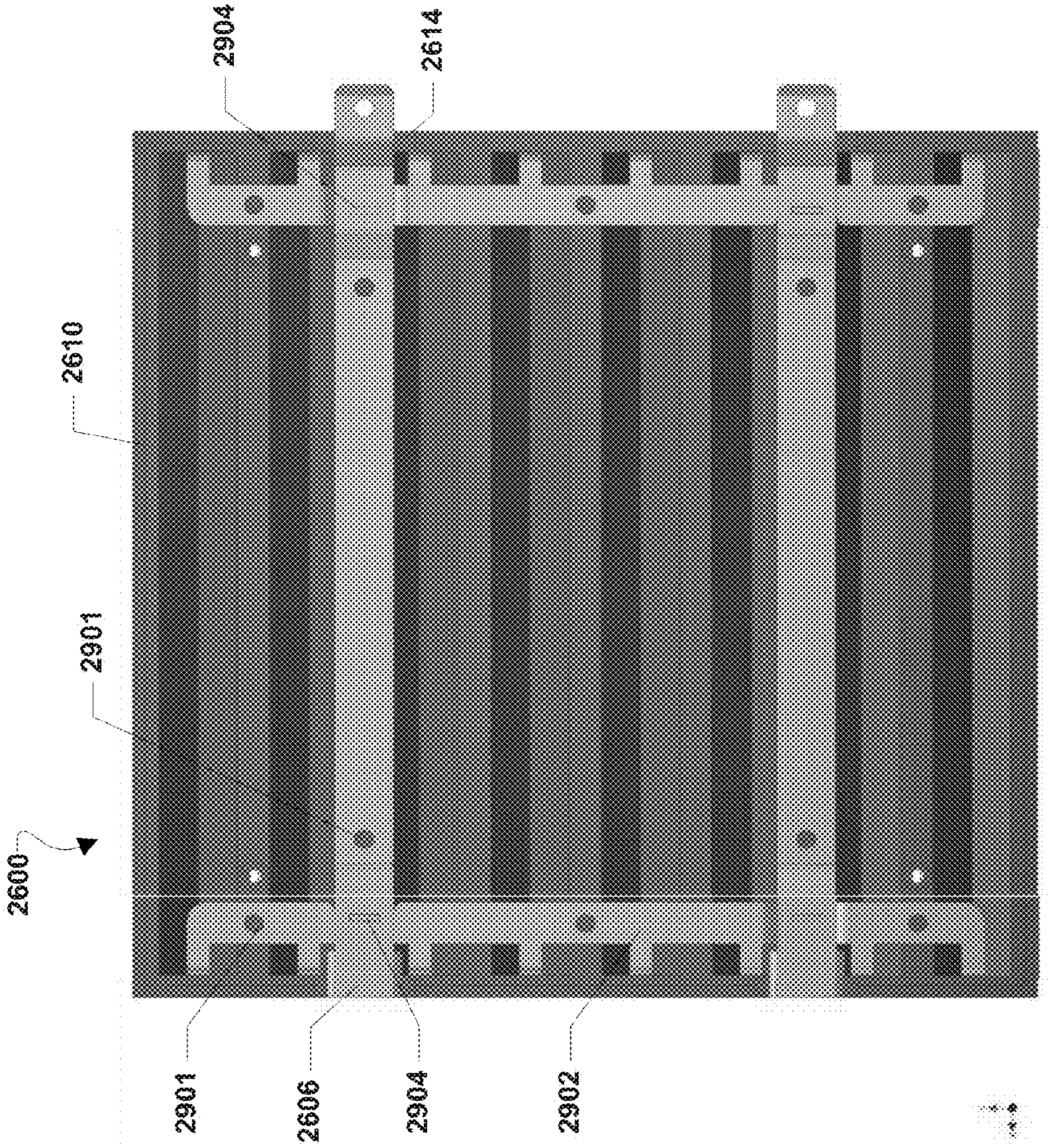

FIG. 30

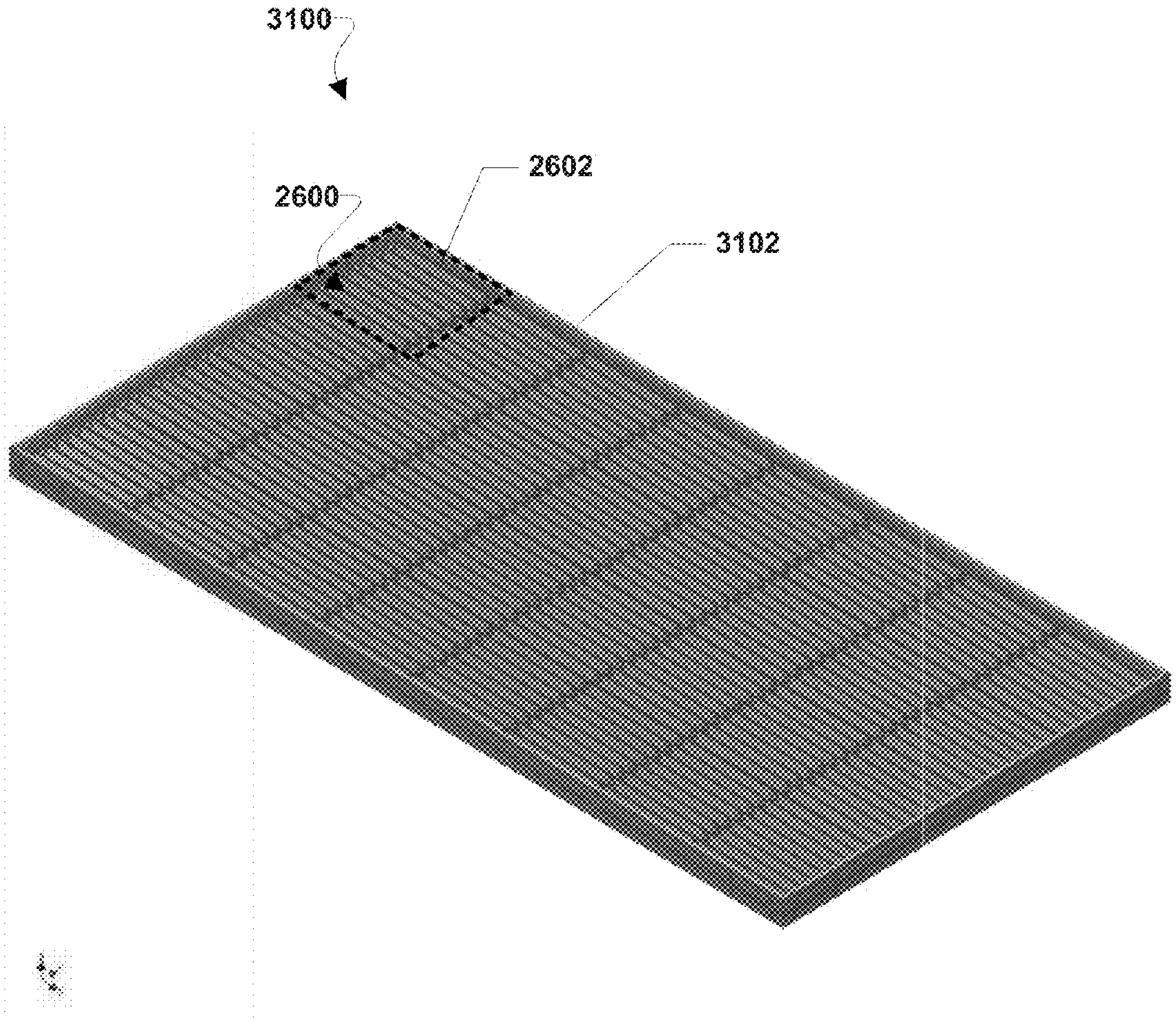

FIG. 31

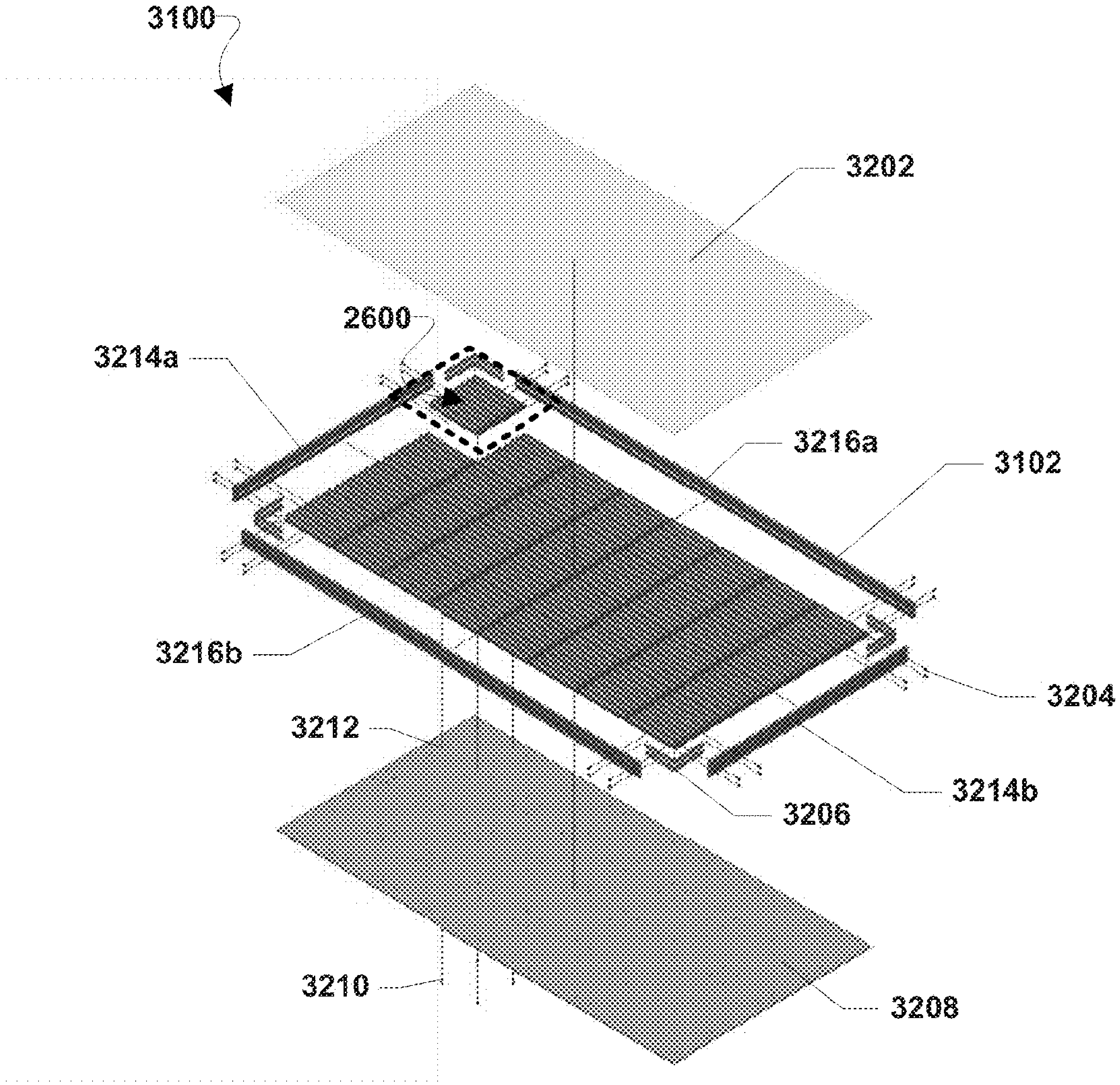
3100
3202
2600
3214a
3216a
3102
3216b
3204
3212
3214b
3206
3210
3208

FIG. 32

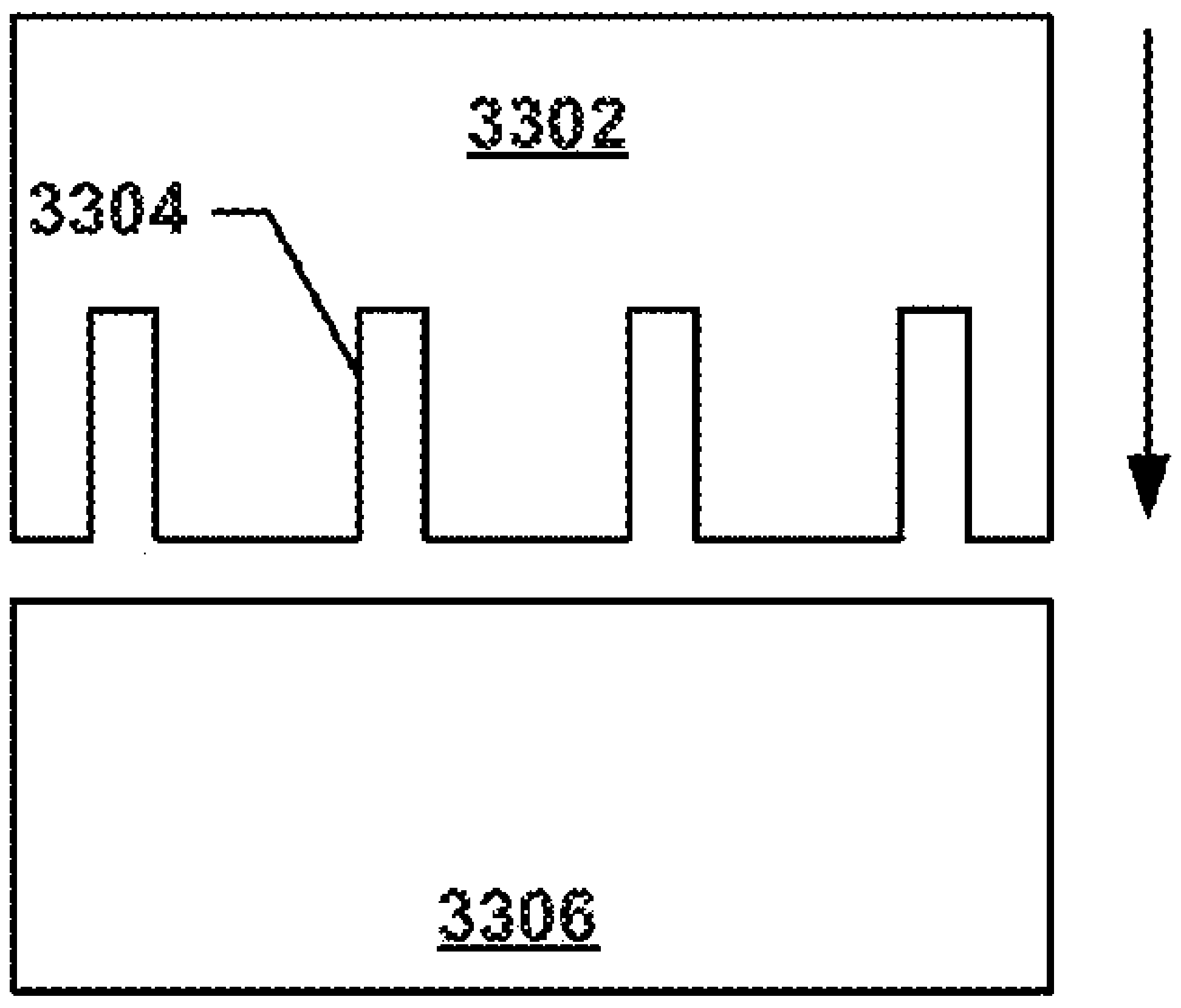

FIG. 33A

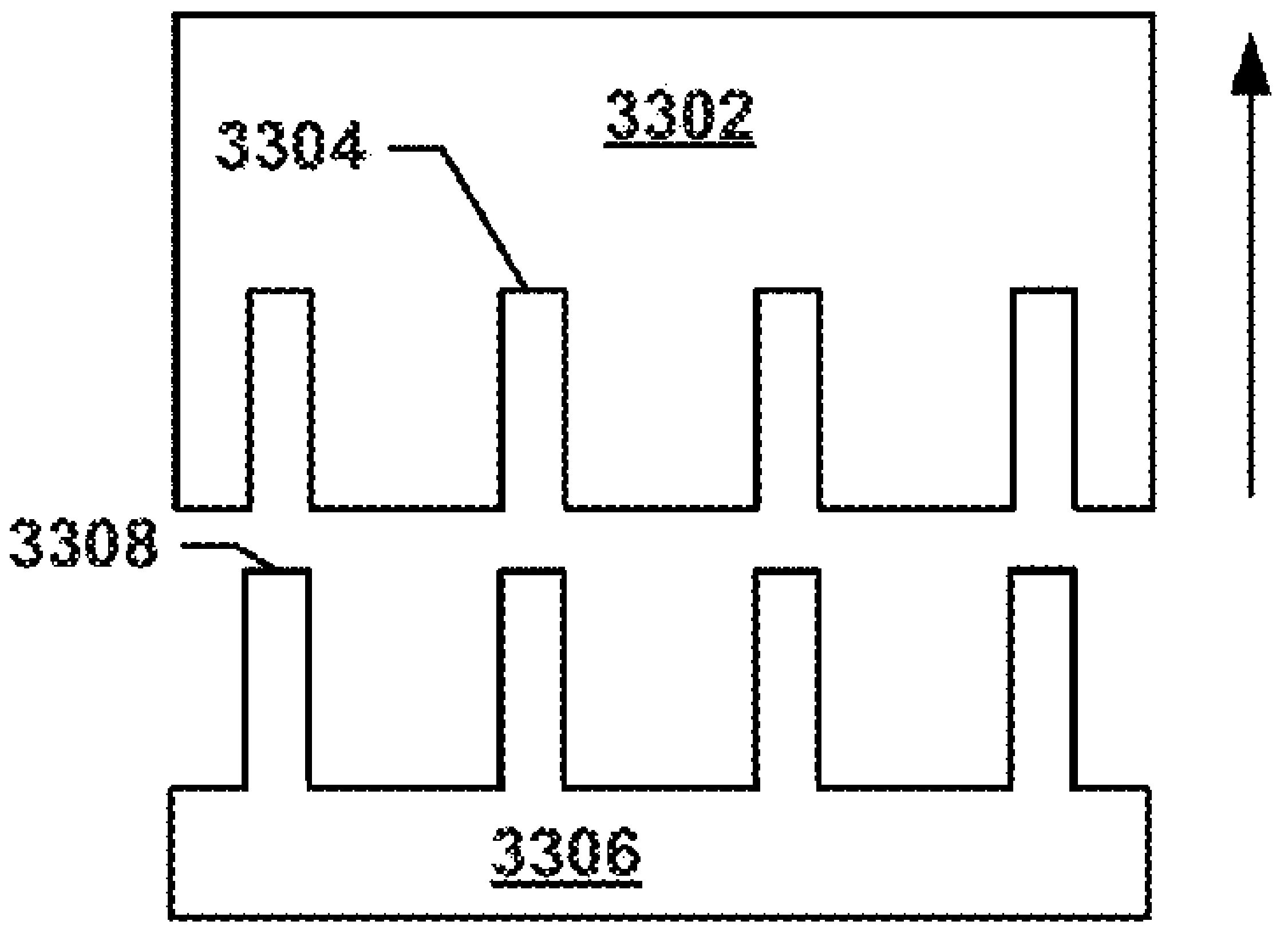

FIG. 33B

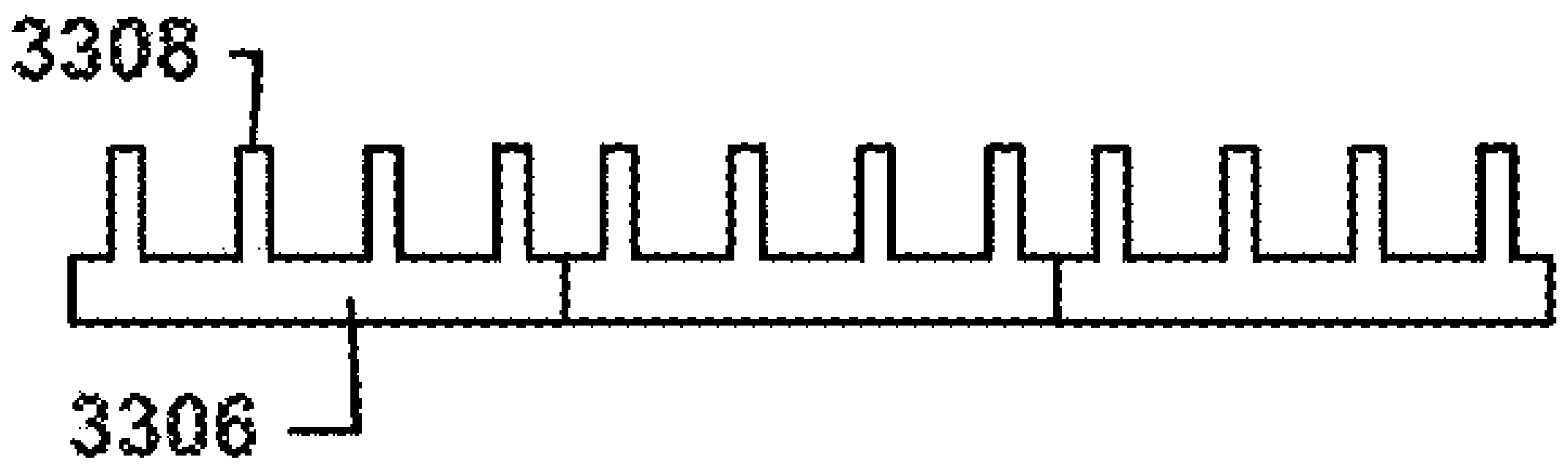

FIG. 33C

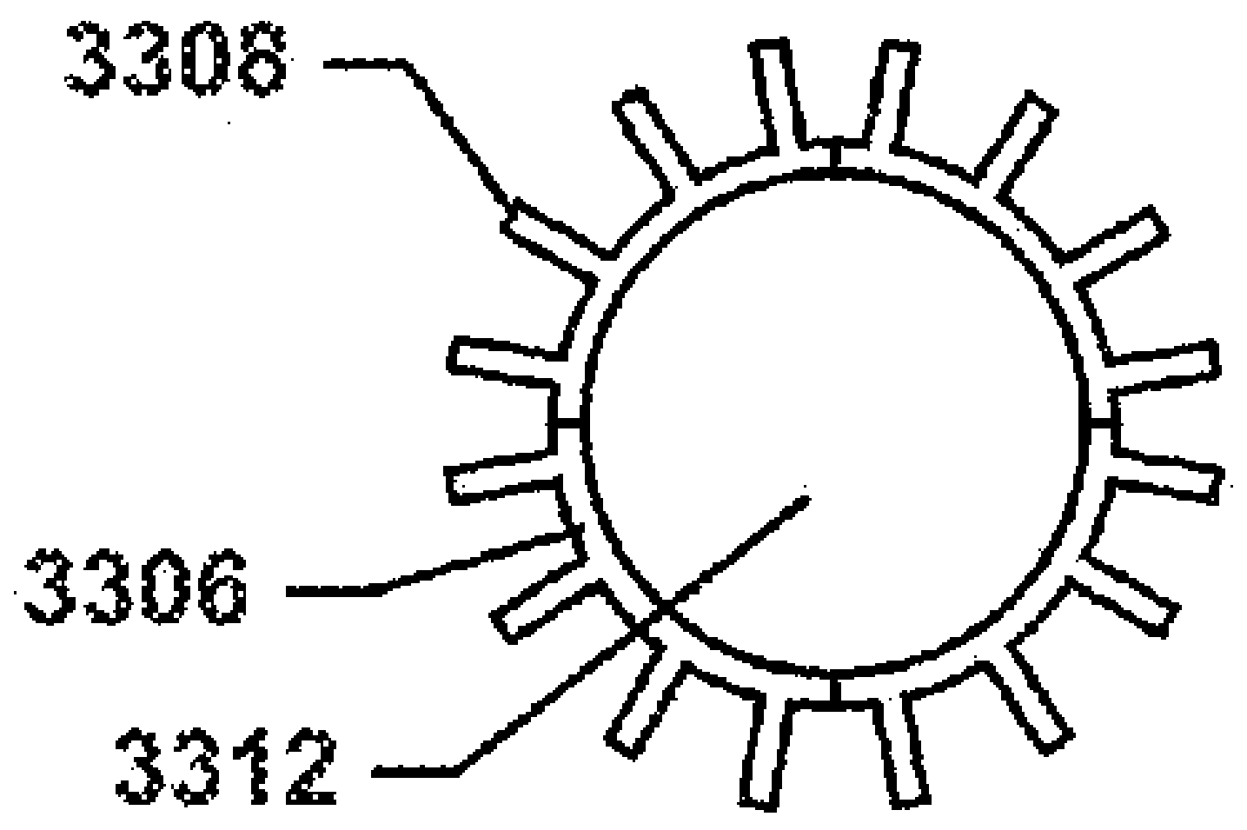

FIG. 33D

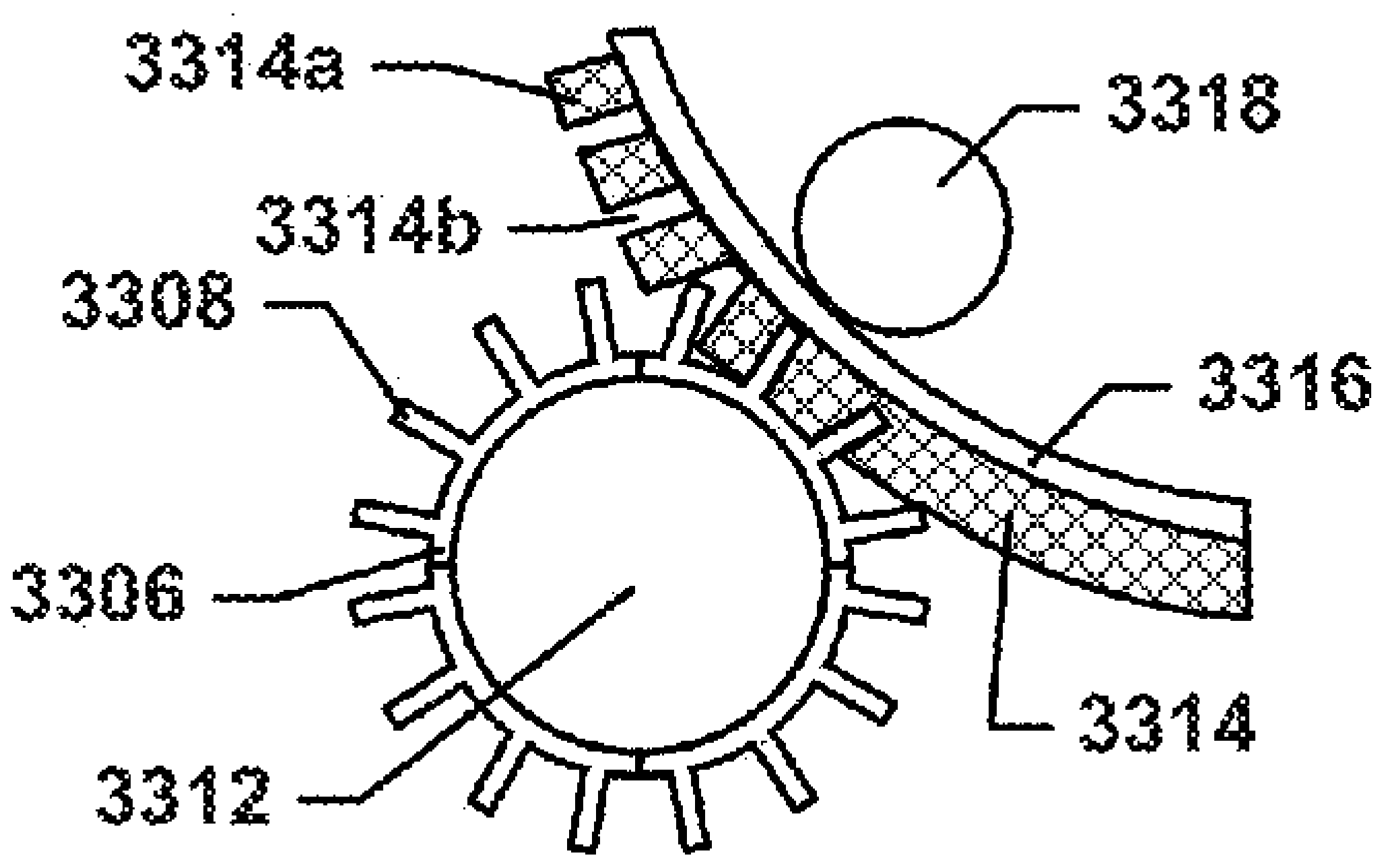

FIG. 33E

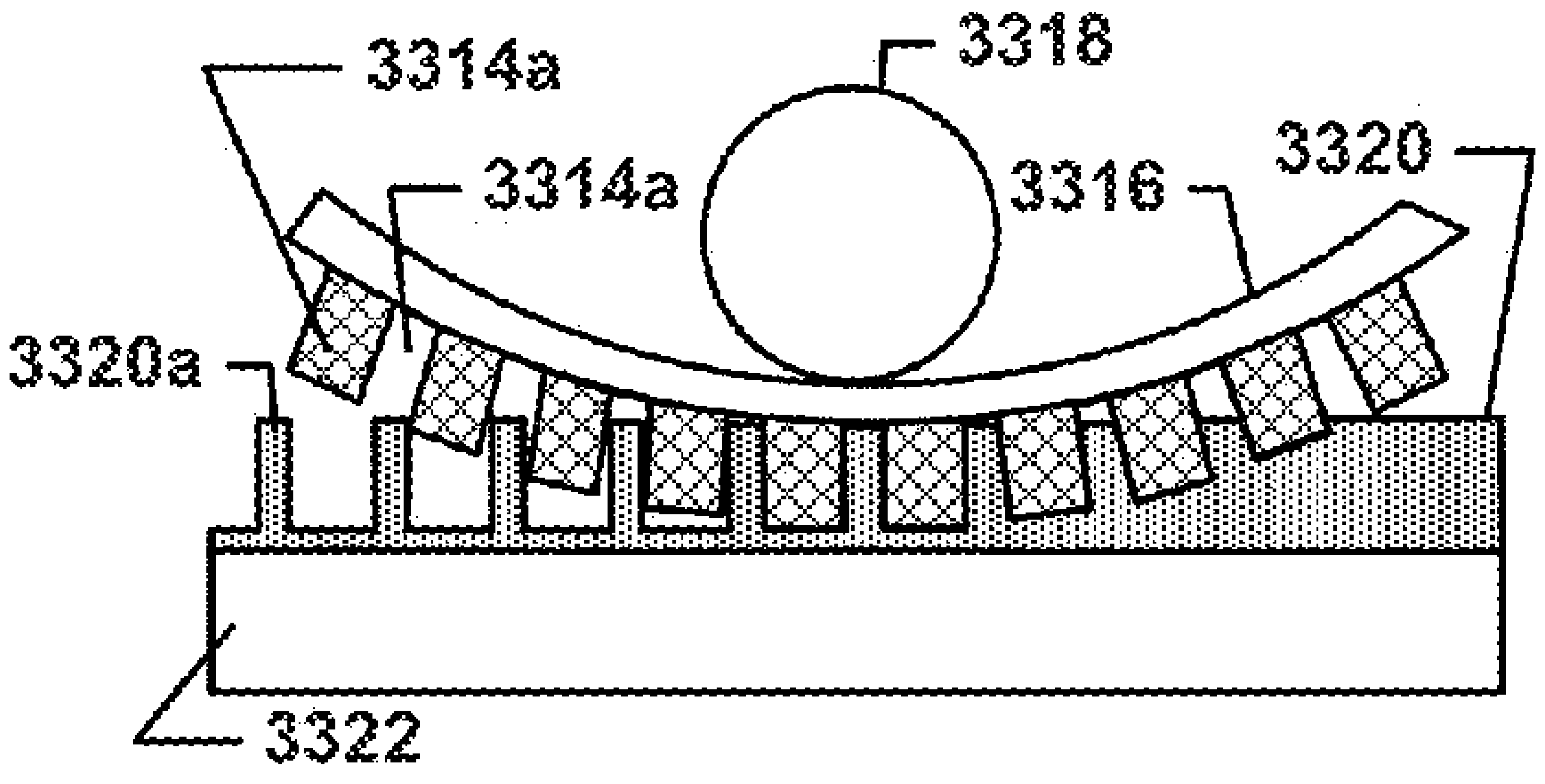

FIG. 33F

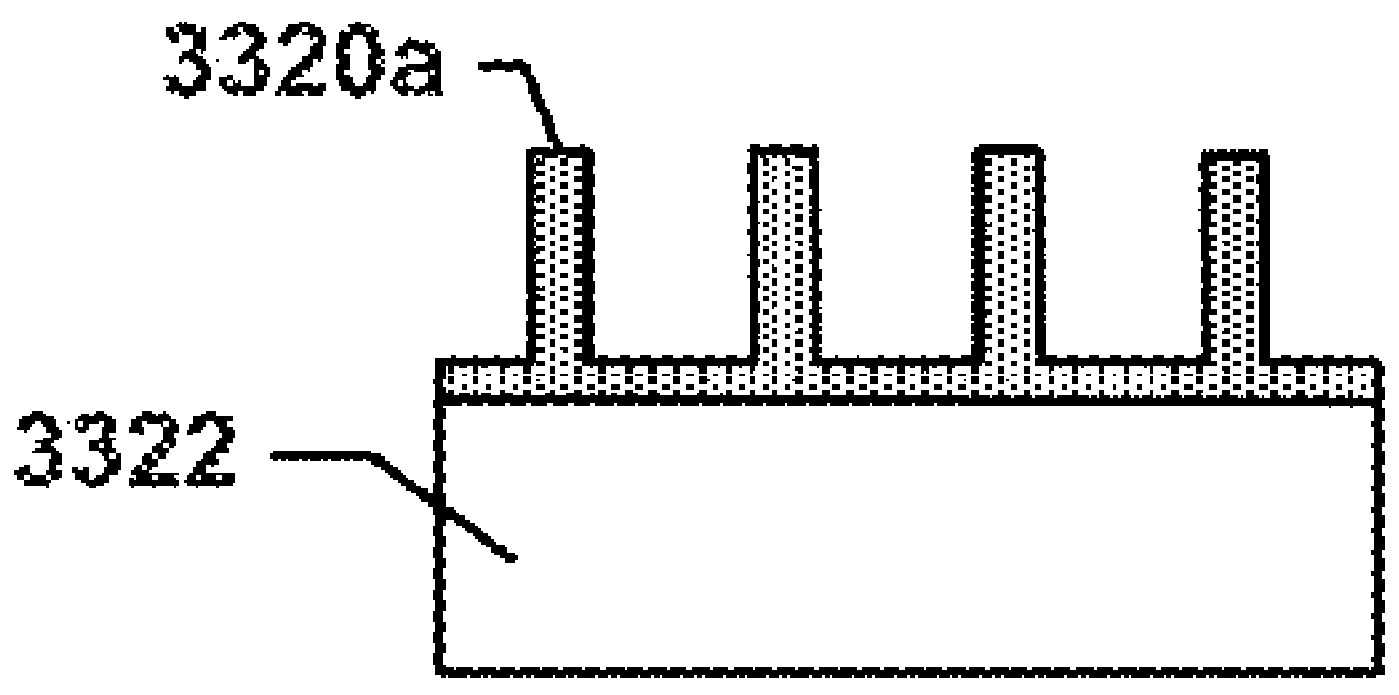

FIG. 33G

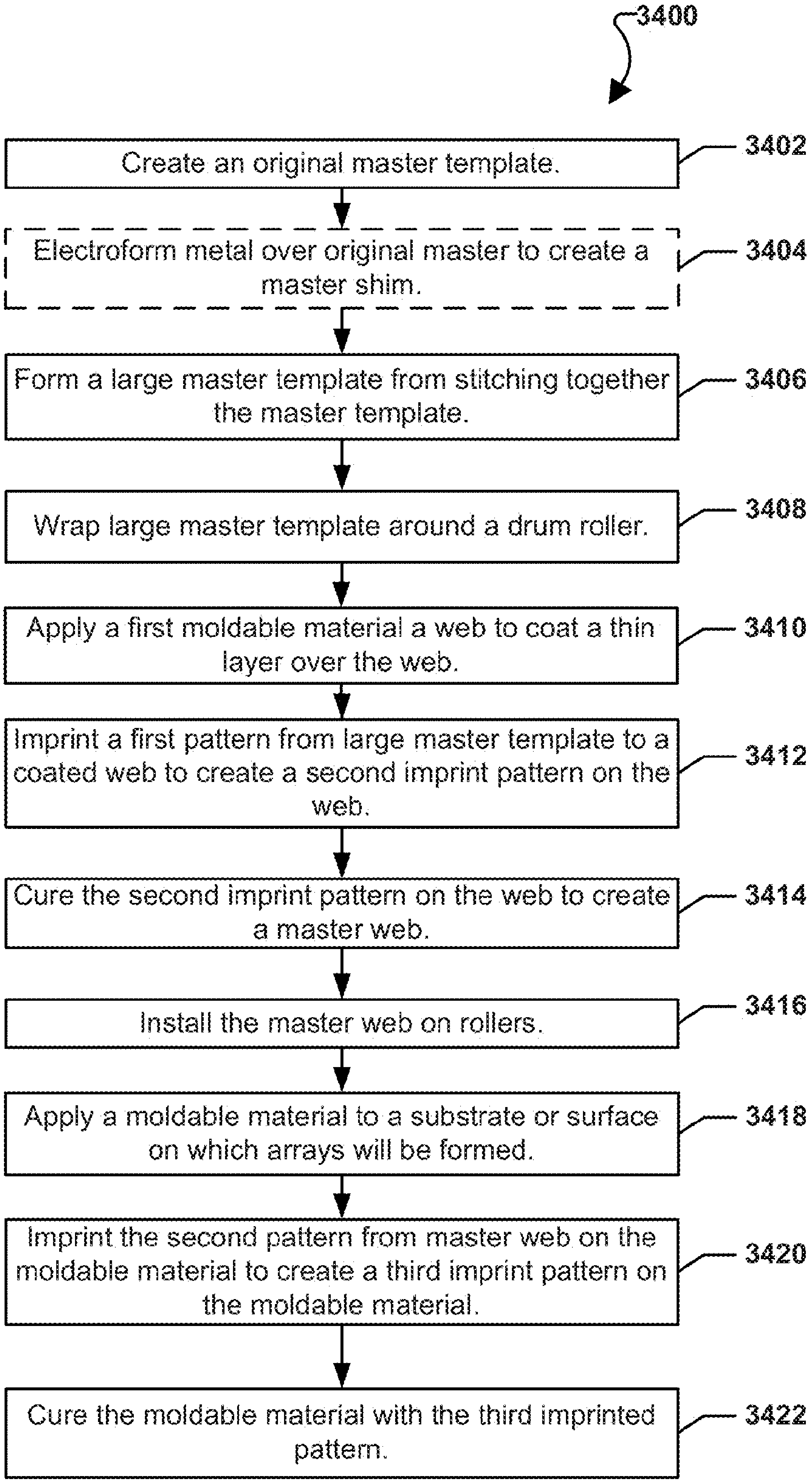
3400
Create an original master template.
3402
Electroform metal over original master to create a master shim.
3404
Form a large master template from stitching together the master template.
3406
Wrap large master template around a drum roller.
3408
Apply a first moldable material a web to coat a thin layer over the web.
3410
Imprint a first pattern from large master template to a coated web to create a second imprint pattern on the web.
3412
Cure the second imprint pattern on the web to create a master web.
3414
Install the master web on rollers.
3416
Apply a moldable material to a substrate or surface on which arrays will be formed.
3418
Imprint the second pattern from master web on the moldable material to create a third imprint pattern on the moldable material.
3420
Cure the moldable material with the third imprinted pattern.
3422

FIG. 34

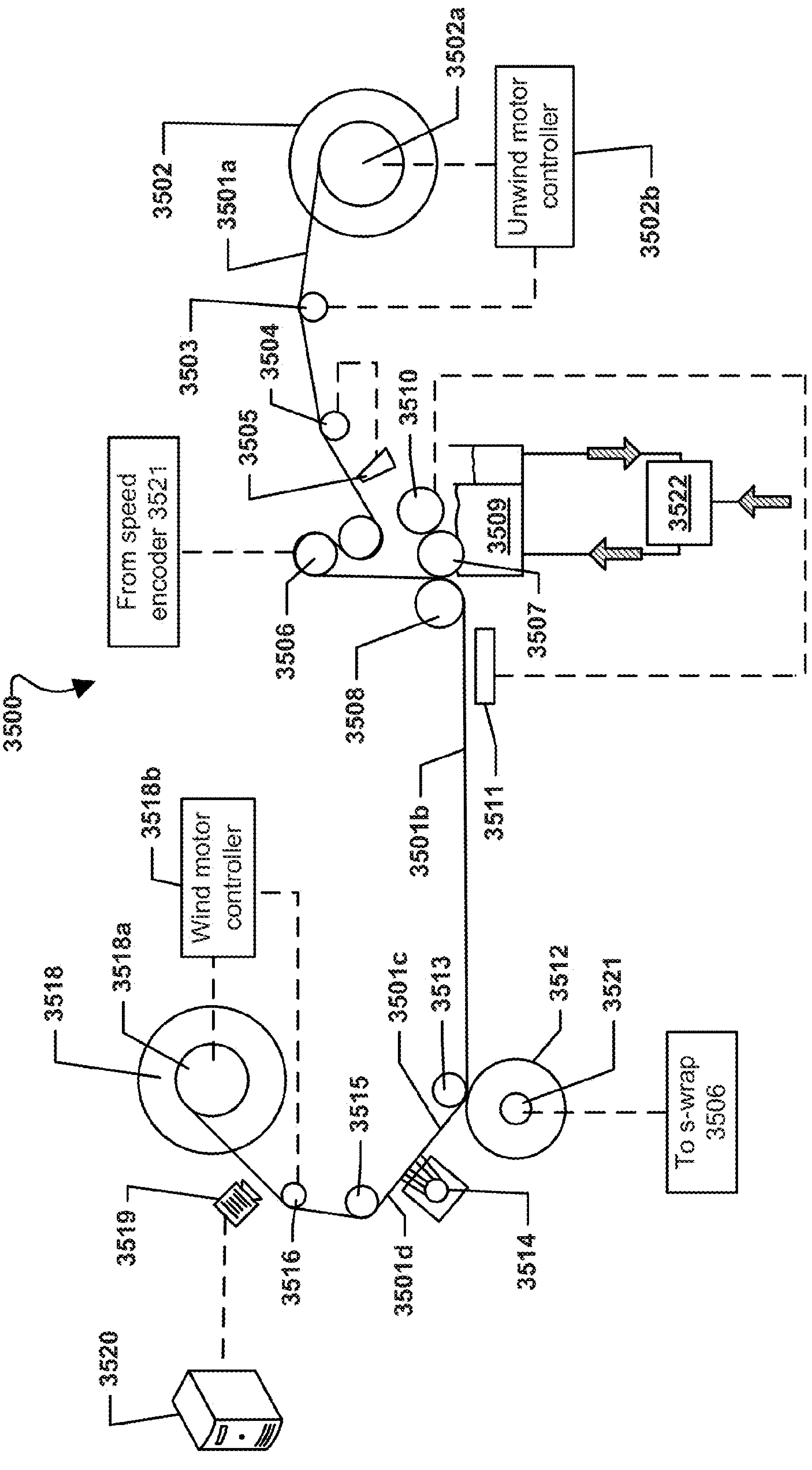
3500
3502
3501a
3502a
Unwind motor controller
3502b
3503
3504
3505
From speed encoder 3521
3510
3509
3522
3506
3507
3508
3511
3501b
3518
3518a
3518b
Wind motor controller
3501c
3513
3512
3521
To s-wrap 3506
3515
3519
3516
3501d
3514
3520

FIG. 35A

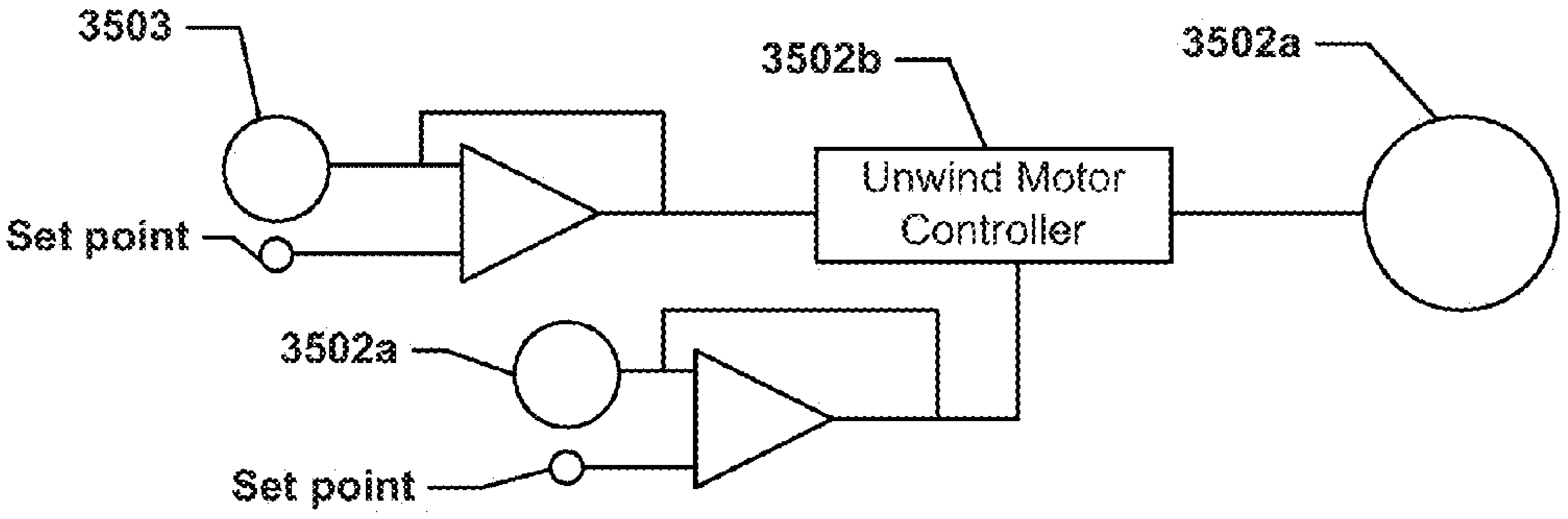

FIG. 35B

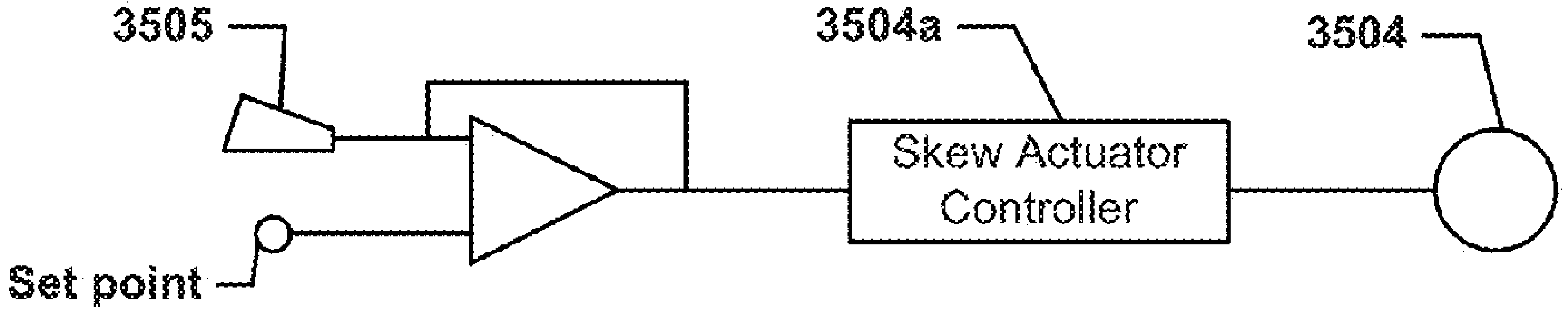

FIG. 35C

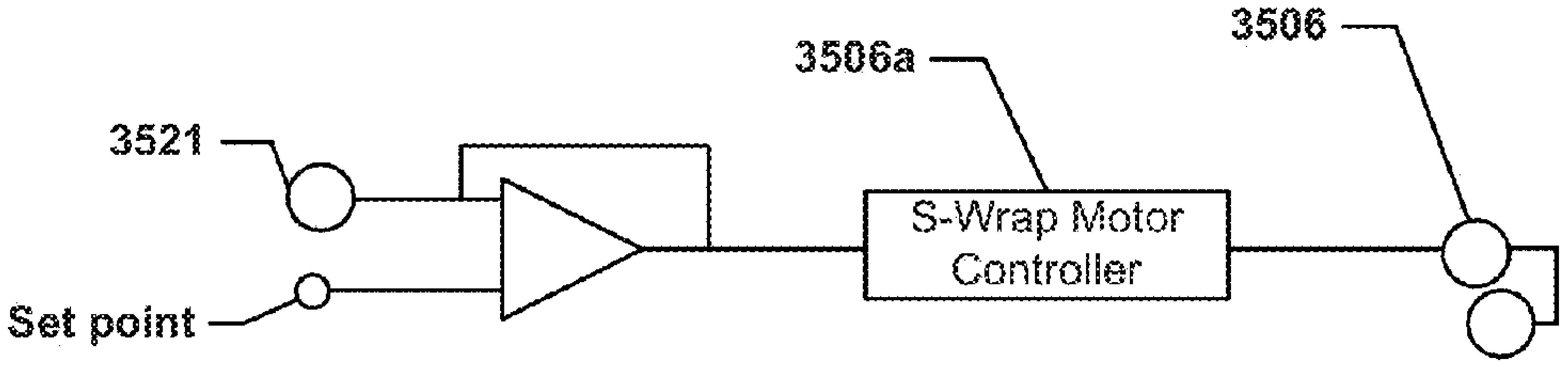

FIG. 35D

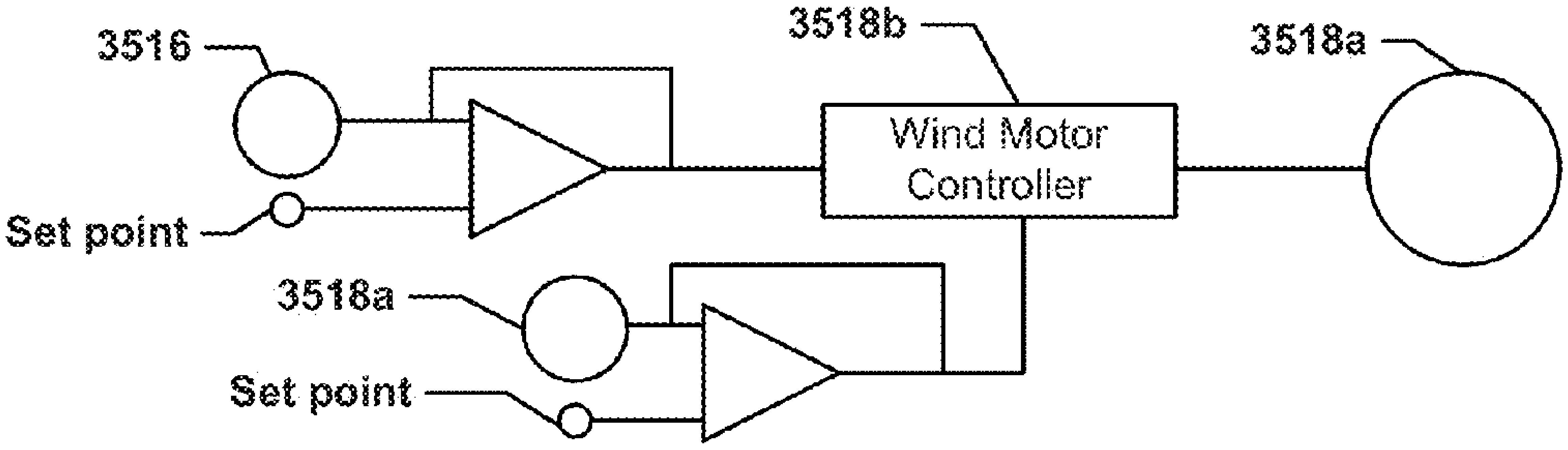

FIG. 35E

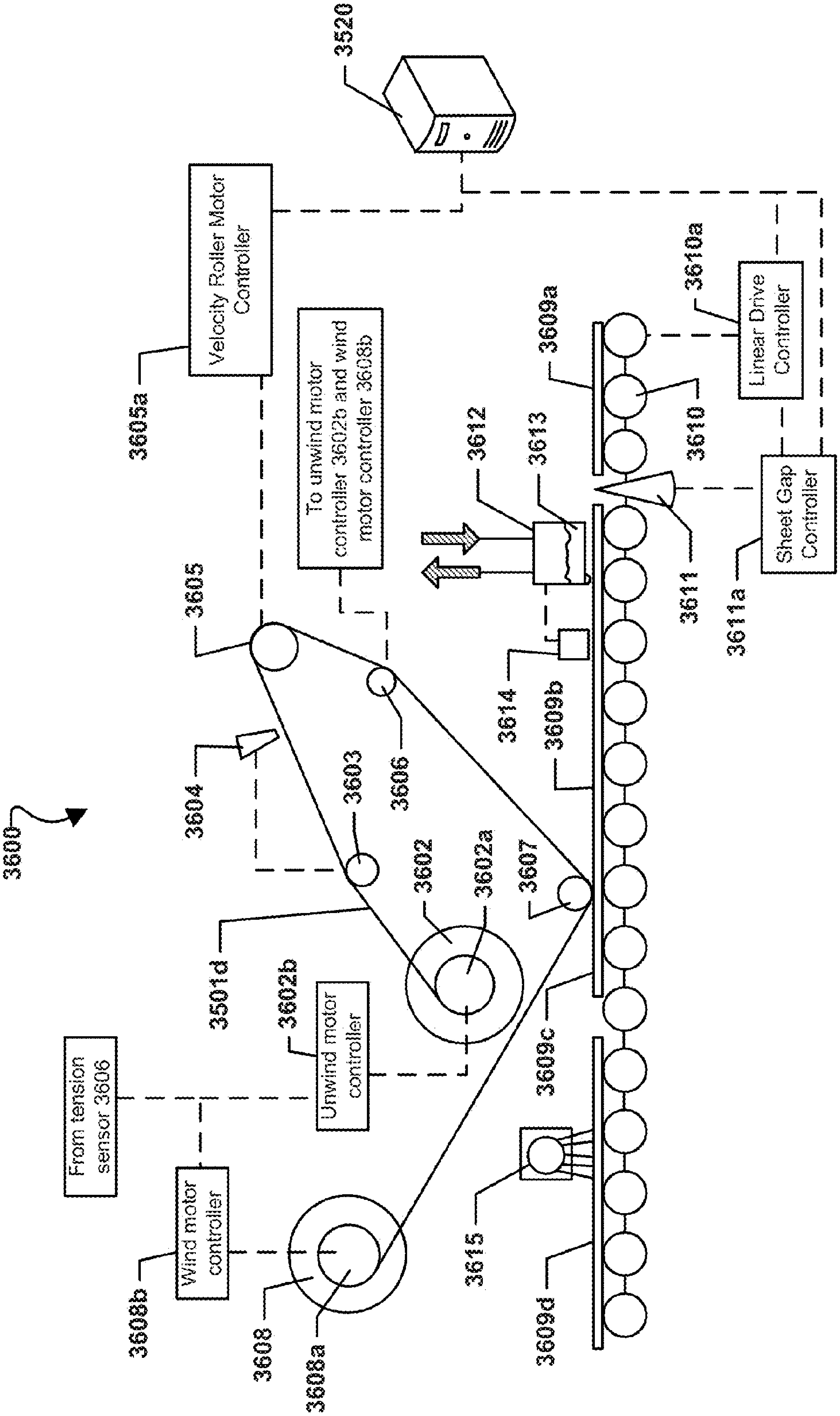
3600
3520
Velocity Roller Motor Controller
3605a
To unwind motor controller 3602b and wind motor controller 3608b
3605
3604
3603
3606
3602
3602a
3501d
3607
Unwind motor controller
3602b
From tension sensor 3606
Wind motor controller
3608b
3608
3608a
3612
3613
3614
3609b
3609c
3615
3609d
3609a
3610
3610a
Linear Drive Controller
3611
3611a
Sheet Gap Controller

FIG. 36A

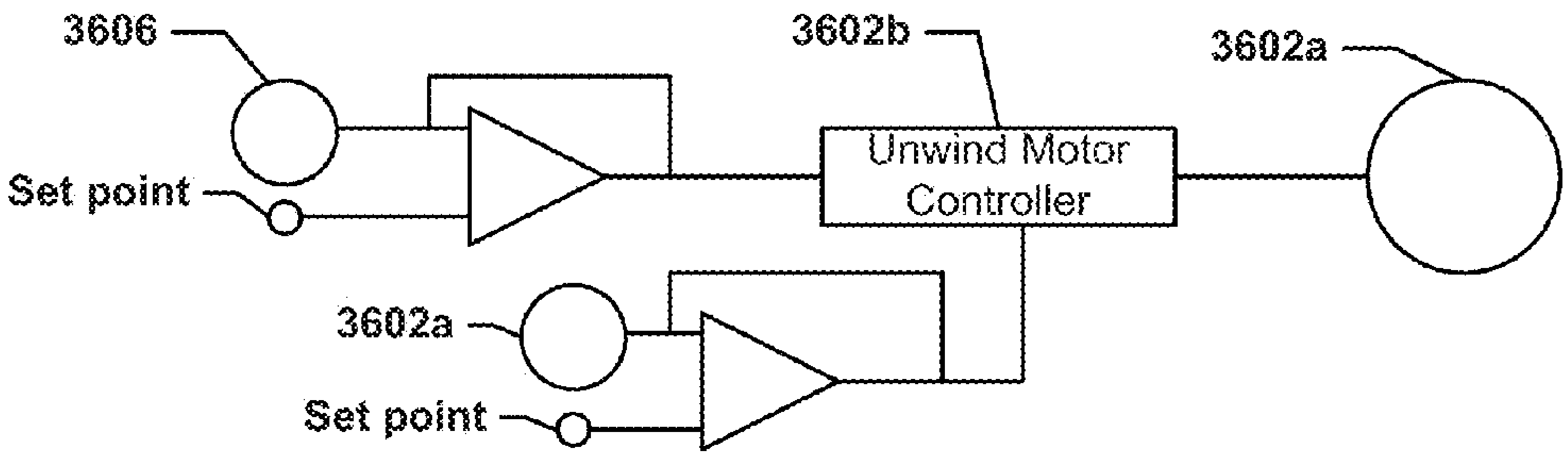

FIG. 36B

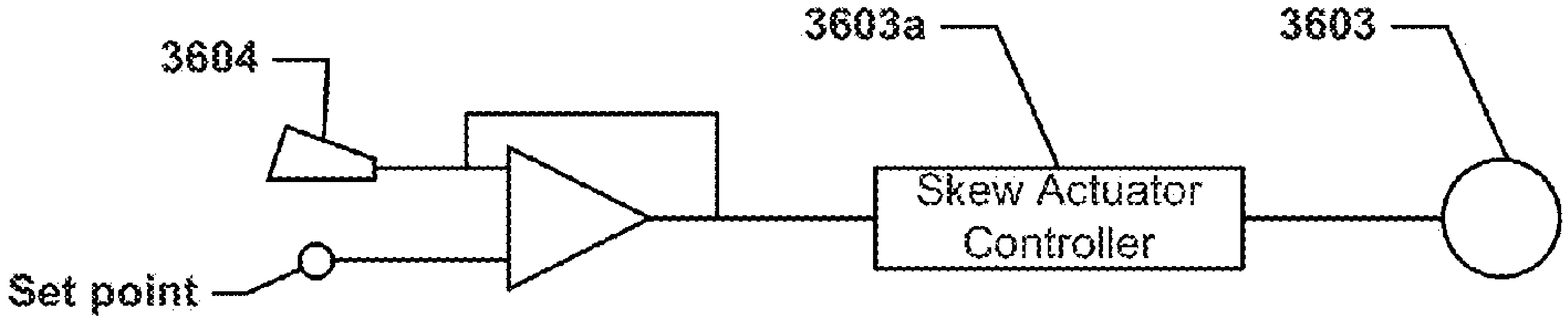

FIG. 36C

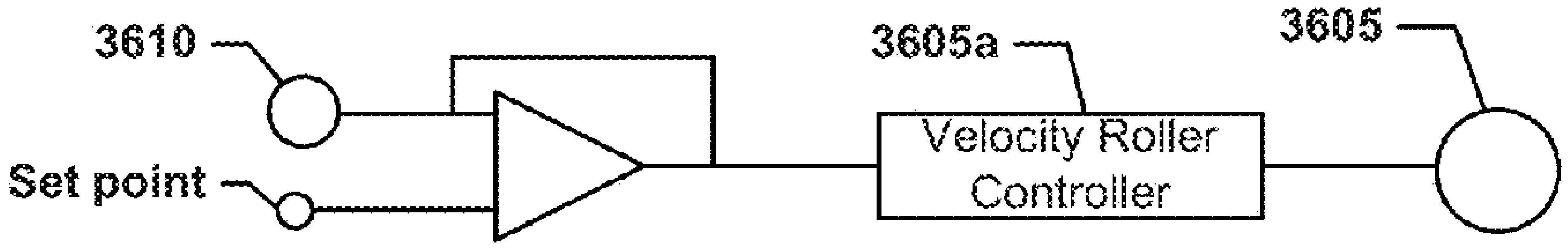

FIG. 36D

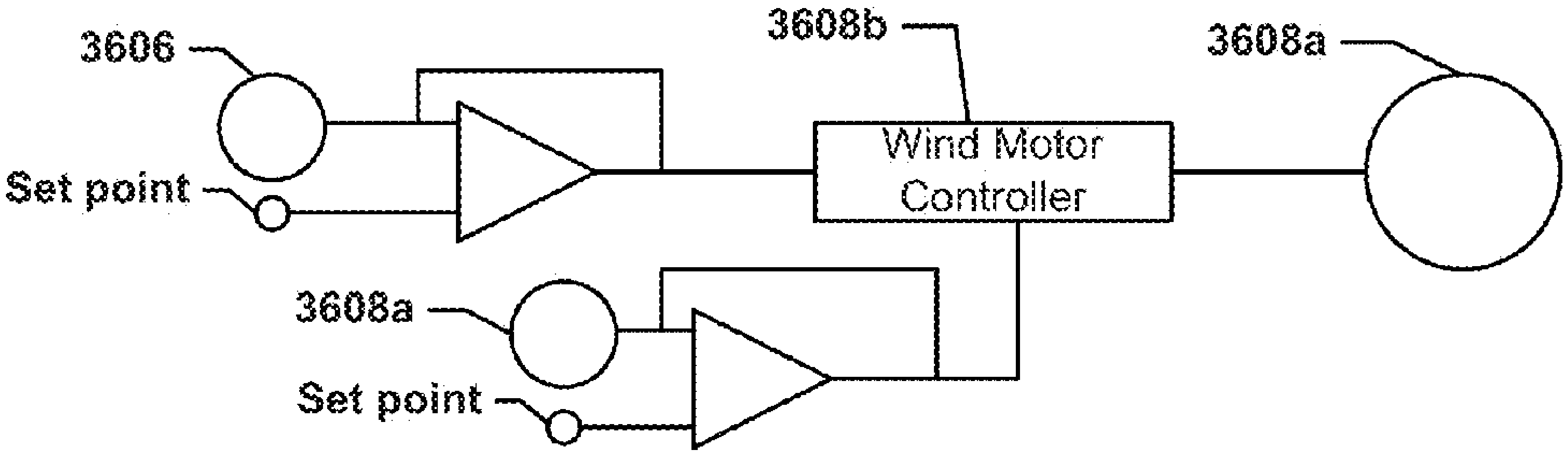

FIG. 36E

METHODS FOR MANUFACTURING THREE-DIMENSIONAL METAMATERIAL DEVICES WITH PHOTOVOLTAIC BRISTLES

RELATED APPLICATIONS

[0001] This application is a continuation-in-part of U.S. patent application Ser. No. 13/830,295, entitled "Methods for Manufacturing Three Dimensional Metamaterial Devices with Photovoltaic Bristles" filed Mar. 14, 2013, the entire contents of which are hereby incorporated by reference. This application is also related to U.S. patent application Ser. No. 13/751,914, entitled "Three-Dimensional Metamaterial Device with Photovoltaic Bristles" filed Jan. 28, 2013, the entire contents of which are hereby incorporated by reference for purposes of disclosing dimensions, materials and configurations of photovoltaic bristles that may be manufactured by the embodiment processes disclosed herein.

FIELD

[0002] This application generally relates to photovoltaic devices, and more specifically to the methods of manufacturing photovoltaic cells featuring a large number of photovoltaic bristles.

BACKGROUND

[0003] Solar power is a popular clean energy, but it is generally more expensive than its fossil fuel competitors (e.g., oil, coal, and natural gas) and other traditional energy sources (e.g., hydropower). Typically, solar energy is relatively expensive because traditional photovoltaic cells with a planar configuration have generally low total efficiency. Total efficiency is based upon the total power produced from a solar panel throughout the day as the sun transits across the sky. Total efficiency is different from the theoretical efficiency, which is the fraction of light energy converted to electricity by the photovoltaic cells with a zero angle of incidence (e.g., the instant when the sun is directly above the metamaterial). Thus, a high total efficiency photovoltaic cell is needed to make solar energy cost-competitive with fossil fuels and traditional energy sources.

SUMMARY

[0004] The various embodiment methods of manufacturing and assembling may be used to produce photovoltaic cells formed from a plurality of photovoltaic bristles whose photovoltaic and conductive materials are configured to exhibit a high probability of photon absorption and internal reflection. As a result of the high probability of photon absorption and internal photon reflections, the photovoltaic cells of photovoltaic bristles exhibit high total efficiency in converting light energy into electrical energy. The high total efficiency of the embodiment photovoltaic cells may lead to increased efficiency and more power generation from the photovoltaic cell.

[0005] In various embodiments, printing techniques may be used to ensure high throughput and low defects in manufacturing the metamaterial device. The high throughput and low defects may reduce the manufacturing cost to enable the embodiment metamaterial devices to reach grid parity. In various embodiments, arrays of cores or vias may be manufactured from an original master template. An embodiment roll-to-web system and method may create daughter templates or master webs from the original master template to protect the original master template from repeat processing, thereby reducing defects. An embodiment web-to-plate system and method may create an array of cores or vias on a substrate from the master web. The master web, or plate, may be subjected to further processing (depositing photovoltaic layers, conductive layers, etc.) to create the embodiment metamaterial device.

BRIEF DESCRIPTION OF THE DRAWINGS

[0006] The accompanying drawings, which are incorporated herein and constitute part of this specification, illustrate exemplary embodiments of the invention, and together with the general description given above and the detailed description given below, serve to explain the features of the invention.

[0007] FIG. **1**A is a cross-sectional top view of an embodiment photovoltaic bristle.

[0008] FIG. **1**B is a cross-sectional side view of an embodiment photovoltaic bristle.

[0009] FIG. **2**A is a perspective view of an embodiment metamaterial of an array of photovoltaic bristles positioned on a flat substrate.

[0010] FIG. **2**B is a cross-sectional side view of an embodiment metamaterial array of photovoltaic bristles positioned on a flat substrate.

[0011] FIG. **3**A is a perspective view of an embodiment metamaterial with arrays of photovoltaic bristles positioned on a corrugated substrate.

[0012] FIG. **3**B is a cross-sectional side view of an embodiment metamaterial with arrays of photovoltaic bristles positioned on a corrugated substrate.

[0013] FIG. **4**A is a perspective view of an embodiment metamaterial with arrays of photovoltaic bristles positioned on alternating slanted substrate surfaces of a corrugated substrate.

[0014] FIG. **4**B is a cross-sectional side view of an embodiment metamaterial with arrays of photovoltaic bristles positioned on alternating slanted substrate surfaces of a corrugated substrate.

[0015] FIG. **5** is an illustration of embodiments shown in FIGS. **2**A, **3**A, and **4**A positioned on the slanted planes of a structure facing away or towards the equator.

[0016] FIGS. **6**A-**6**H are cross-sectional side views illustrating an embodiment method for forming an array of photovoltaic bristles for a metamaterial device stamping process.

[0017] FIGS. **6**I-**6**K are cross-sectional side views illustrating an embodiment method for forming an array of photovoltaic bristles using a molding process.

[0018] FIGS. **7**A, **7**B, and **7**C are side views of a molding process embodiment for forming a substrate and form arrays of cores on the shaped substrate.

[0019] FIG. **8** is a process flow diagram illustrating the embodiment methods illustrated in FIGS. **6**A-**6**K and **7**A-**7**C.

[0020] FIGS. **9**A-**9**J are cross-sectional side views illustrating an embodiment method a plating process to form an array of bristles for a metamaterial device.

[0021] FIG. **10** illustrates an embodiment plating method for forming the embodiment metamaterials.

[0022] FIGS. **11**A-**11**L are cross-sectional side views illustrating an embodiment method for forming the embodiment metamaterial by creating vias using photolithographic and etching techniques and subsequently removing the original substrate.

[0023] FIG. **12** is a process flow diagram illustrating the embodiment method for forming the embodiment metamaterials illustrated in FIGS. **11**A-**11**L.

[0024] FIGS. **13**A-**13**L are cross-sectional side views illustrating an embodiment method for forming the embodiment metamaterial by creating vias using photolithographic and etching techniques while leaving the etched substrate intact.

[0025] FIGS. **13**M-**13**O are cross-sectional side views illustrating an alternative embodiment method for creating vias using lasers.

[0026] FIG. **14** is a process flow diagram of the embodiment method illustrated in FIGS. **13**A-**13**L.

[0027] FIGS. **15**A-**15**J are cross-sectional side views illustrating an embodiment method for forming the embodiment metamaterial by creating vias using a stamping method and leaving the substrate intact.

[0028] FIGS. **15**K-**15**M are cross-sectional side views for forming the embodiment metamaterial by molding a substrate and leaving the substrate intact.

[0029] FIG. **16** is a process diagram of the embodiment method for forming the metamaterial illustrated in FIGS. **15**A-**15**J.

[0030] FIG. **17** is a cross-sectional side view of an array of photovoltaic bristles positioned on a flat substrate with current conducting traces on top of short photovoltaic bristles.

[0031] FIG. **18** is a top view of the metamaterial of FIG. **17**.

[0032] FIG. **19** is a cross-sectional side view of an array of photovoltaic bristles positioned on a flat substrate with current conducting traces between photovoltaic bristles.

[0033] FIG. **20** is a top view of metamaterial of FIG. **19**.

[0034] FIG. **21** is a cross-sectional side view of an array of photovoltaic bristles positioned on a corrugated substrate with current conducting traces between photovoltaic bristles.

[0035] FIGS. **22**A-**22**H are cross-sectional side views illustrating methods for adding current conducting traces to the outer conductive layer of a metamaterial.

[0036] FIG. **23** is a process flow diagram of the embodiment method for depositing current conducting traces on the outer conductive layer of a metamaterial illustrated in FIGS. **22**A-**22**H.

[0037] FIGS. **24**A-**24**J are cross-sectional side views illustrating methods for adding current conducting traces to an inner conductive layer of a metamaterial.

[0038] FIGS. **24**K-**24**M are cross-sectional side views of methods using a laser prior to adding current conducting traces to an inner conductive layer of a metamaterial.

[0039] FIG. **25** is a process flow diagram of the embodiment method for depositing current conducting traces on an inner conductive layer of a metamaterial illustrated in FIGS. **24**A-**24**J.

[0040] FIG. **26** is a perspective view of embodiment metamaterials in a solar panel section including a corrugated base.

[0041] FIG. **27** is a top view of a section of a solar panel with a corrugated base According to an embodiment.

[0042] FIG. **28** is a side view of a section of a solar panel with a corrugated base according to an embodiment.

[0043] FIG. **29** is an exploded view of a section of a solar panel with a corrugated base according to an embodiment.

[0044] FIG. **30** is a back view of a section of a solar panel with a corrugated base according to an embodiment.

[0045] FIG. **31** is a perspective view of a solar panel according to an embodiment.

[0046] FIG. **32** is an exploded view of a solar panel according to an embodiment.

[0047] FIGS. **33**A-**33**G are cross-sectional side views illustrating an embodiment method for forming an array of photovoltaic bristles for a metamaterial device stamping process.

[0048] FIG. **34** is a process flow diagram illustrating the embodiment method illustrated in FIGS. **33**A-**33**G.

[0049] FIG. **35**A is a system diagram illustrating an embodiment roll-to-web system.

[0050] FIGS. **35**B-**35**E are logic diagrams corresponding to the roll-to-web system illustrated in FIG. **35**A.

[0051] FIG. **36**A is a system diagram illustrating an embodiment web-to-plate system.

[0052] FIGS. **36**B-**36**E are logic diagrams corresponding to the web-to-plate system illustrated in FIG. **36**A.

DETAILED DESCRIPTION

[0053] The various embodiments will be described in detail with reference to the accompanying drawings. Wherever possible, the same reference numbers will be used throughout the drawings to refer to the same or like parts. References made to particular examples and implementations are for illustrative purposes, and are not intended to limit the scope of the invention or the claims. Any reference to claim elements in the singular, for example, using the articles “a,” “an,” or “the” is not to be construed as limiting the element to the singular. The terms “example,” “exemplary,” or any term of the like are used herein to mean serving as an example, instance, or illustration. References to particular examples and implementations are for illustrative purposes, and are not intended to limit the scope of the invention or the claims. Any implementation described herein as an “example” is not necessarily to be construed as preferred or advantageous over another implementation.

[0054] As used herein, the term “photovoltaic bristle” refers to a three-dimensional structure approximately cylindrical with a height approximately equal to 1-100 microns, a diameter of approximately 0.2-50 microns that includes at least one photovoltaically-active semiconductor layer sandwiched between a conductive inner layer or core and a transparent outer conductive layer (e.g., TCO and a nonconductive outerlayer). The term “bristle” is used merely because the structures have a length greater than their diameter, the structures have a generally (on average) circular cross-section, and the overall dimensions of the structures are on the dimensions of sub-microns to tens of microns. In the embodiment illustrated herein the photovoltaic bristles have an approximately cylindrical shape, by which it is meant that a substantial portion of the exterior surface of the structures have a cross-section that is approximately circular or elliptical with both radii being approximately coexistent. Due to manufacturing variability, no single photovoltaic bristle may be exactly cylindrical in profile, but when considered over a large number of photovoltaic bristles the average profile is approximately cylindrical. In another embodiment, the photovoltaic bristles may have a non-circular cross-section, such as hexagonal, octagonal, elliptical, etc. as may facilitate manufacturing.

[0055] When the embodiment photovoltaic bristles are arranged on a substrate in an order or disordered array, the resulting structure may form a metamaterial structure. As used herein, the term “metamaterial” or “metamaterial substrate” refers to an array of photovoltaic bristles on a substrate. Metamaterials as used herein are artificial materials that are engineered with metals or polymers that are arranged in a particular structured or non-structured pattern that result in material properties (including light absorption and refraction properties) that are different from the component materials. The cumulative effect of light interacting with the array of photovoltaic bristles may be affected by controlling the shape, geometry, size, orientation, material properties, material thicknesses, and arrangement of the bristles making up the metamaterial as described herein.

[0056] Traditional planar photovoltaic cells are flat. In traditional planar photovoltaic cells, a limited number of photons are absorbed at any given point in time. Photon absorption occurs through the thickness of the traditional planar photovoltaic cell (e.g., top-to-bottom) from the point of photon entry until the photon is converted to electrical energy. Traditional planar photovoltaic cells convert photons into electrical energy when photons interact with a photovoltaic layer. However, some photons pass through the photovoltaic layer without generating electron-hole pairs, and thus represent lost energy. While the number of photons absorbed may be increased by making the photovoltaic layer thicker, increasing the thickness increases the fraction of electron-hole pairs that recombine, converting their electrical potential into heat. Additionally, thicker photovoltaic films exhibit an exponential attenuation loss leading to a decrease in photon conversion. For this reason, traditional planar photovoltaic cells have emphasized thin photovoltaic layers, accepting the reduced photon-absorption rate in favor of increased conversion of electron-hole pairs into electrical current and reduced heating. The theoretical peak efficiency, as well as the total efficiency, of traditional planar photovoltaic cells is thus limited by the planar geometry and the un-attenuated fraction of photons that can be absorbed in a maximized optical path length through the photovoltaic layer.

[0057] Conventional planar photovoltaic cells also suffer from low total efficiency in static deployments (i.e., without sun tracking equipment), since their instantaneous power conversion efficiency decreases significantly when the sun is not directly overhead (i.e., before and after noon). Peak efficiencies of traditional planar photovoltaic cells are affected by their orientation with respect to the sun, which may change depending on the time of day and the season. The standard test conditions for calculating peak efficiencies of solar cells are based on optimum conditions, such as testing the photovoltaic cells at solar noon or with a light source directly above the cells. If light strikes traditional photovoltaic cells at an acute angle to the surface (i.e., other than perpendicular to the surface) the instantaneous power conversion efficiency is much less than the peak efficiency. Traditional planar photovoltaic cells in the northern hemisphere are typically tilted toward the south by an angle based on the latitude in order to improve their efficiency. While such fixed angles may account for the angle of the sun at noon due to latitude, the photovoltaic cells receive sunlight at an angle during the morning and afternoon (i.e., most of the day). Thus, traditional planar photovoltaic cells actually result in a low total efficiency and low total power generation when measured beyond a single moment in time.

[0058] The various embodiments include photovoltaic cells that exhibit metamaterial characteristics from regular or irregular arrays of photovoltaic bristles configured so the conversion of light into electricity occurs within layers of the photovoltaic bristles. Since the photovoltaic bristles extend above the surface of the substrate and are spaced apart, the arrays provide the photovoltaic cells of the various embodiments with volumetric photon absorption properties that lead to energy conversion performance that exceeds the levels achievable with traditional planar photovoltaic cells. The volumetric photon absorption properties enable the various embodiment photovoltaic cells to generate more power than traditional planar photovoltaic cells with the same footprint. Due to the small size of the photovoltaic bristles, the photovoltaically-active layers within each bristle are relatively thin, minimizing power losses due to electron-hole recombination. The thin photovoltaically-active layers help reduce attenuation losses normally present in thicker photovoltaic films because the photovoltaic bristles include a thin radial absorption depth and a relatively thicker vertical absorption depth maximizing photon absorption and power generation through the combined long circumferential absorption path length and short radial electron path length. When individual photovoltaic bristles are combined in an array on, or within, a substrate, a metamaterial structure may be formed that exhibits a high probability of photon absorption and internal reflection that leads to increased energy conversion efficiencies and power generation. Various embodiment structures also provide additional performance-enhancing benefits as will be described in more detail below.

[0059] Further performance enhancements may be obtained by positioning the embodiment photovoltaic cells so that the photovoltaic bristles' sidewalls are at an angle to the incident photons. This can improve the probability that photons will be absorbed into the photovoltaic bristles due to wave interactions between photons and the outer conductive layer on each photovoltaic bristle. Orienting the embodiment photovoltaic bristles at an angle to the incident photons also increases the circumferential optical depth of the photovoltaic bristles exposed to the light, since in such an orientation the photons strike the sides of the bristles and not just the tops. The off-axis photon absorbing characteristics of the photovoltaic bristles also enables the embodiment photovoltaic cells to exhibit significant total energy conversion efficiency for indirect and scattered light, thereby increasing the number of photons available for absorption compared to a conventional photovoltaic cell.

[0060] An embodiment described herein includes photovoltaic cells featuring arrays of photovoltaic bristles on roughly corrugated surfaces in order to present the bristles at an angle to incident sunlight. Further embodiments described herein include methods for manufacturing photovoltaic cells featuring arrays of photovoltaic bristles, as well as assembly of such photovoltaic cells into solar panels.

[0061] For purposes of background on the physics and geometries that enable photovoltaic bristles to achieve significant improvements in peak power performance, an overview of embodiment photovoltaic bristles and corresponding photovoltaic cells is now presented. More details on the dimensions, materials and configurations of embodiment photovoltaic bristles are disclosed in U.S. patent application Ser. No. 13/751,914 that is incorporated by reference above.

[0062] FIG. **1**A illustrates a cross-sectional top view of one photovoltaic bristle **101** and FIG. **1**B illustrates a cross-sectional side view of the photovoltaic bristle **101** of FIG. **1**A. FIGS. **1**A and **1**B illustrate the path traveled by a photon entering the side of the outer periphery of the photovoltaic bristle **101**. A photovoltaic bristle **101** may guide an absorbed photon **112** so that it follows an internal path **113** that exhibits a high probability that the photon remains within the photovoltaic bristle **101** due to total internal reflection. A photovoltaic bristle may exhibit total internal reflection by controlling the thickness of the layers **103** and **111** and by radially ordering the materials by indexes of refractions from a low index of refraction on the outside to a higher index of reaction in each inner layer, the photovoltaic bristle **101** may refract or guide photons **112** toward the core of the photovoltaic bristle **101**. Since the core **106** may be highly conductive, it is also highly reflective, so that it will reflect photons **112**. As illustrated, due to the large difference in index of refraction between the absorber layer and the outer conductive layer **103**, photons striking this boundary at an angle will be refracted inward. As a result of these reflections and refractions, photons **112** may be effectively trapped within the absorption layer **111** for a longer period of time, thereby increasing the probability of interaction with the absorption layer **11** causing an electron-hole pair to be formed. Increasing the probability of photon absorption may result in more electrical current being generated for the same amount of incident light energy by the embodiment photovoltaic cells than is achievable by conventional photovoltaic cells.

[0063] It should be noted that the embodiment shown in FIGS. **2A-2B** may include an inner reflector due to a metal core **106**. In other embodiments, a refraction layer may be applied over the core **106** to achieve the same photon reflection effects. In such an embodiment, a reflective layer may be formed over the conductive core and under the absorber layer, such as a semiconductor or dielectric material layer having a lower index of refraction than the absorber layer. This refraction layer may be configured to reflect the photon at the interface between the reflection layer and the absorber layer, and not rely on reflection off of the conductive core **106**. For example, such a diffraction layer may be formed from an aluminum doped zinc oxide layer of about 500-1500 angstroms in thickness. Reflected photons then refract through each layer **104**, **105** until they reach the outer conductive layer **103**, where the difference in the index of refraction between the absorption sublayer **105** and the outer conductive layer **103** causes the photons to reflect back into the absorption layers of the photovoltaic bristle. The reflected photons that are not reflected inwardly at the boundary between the outer conductive layer **103** and the absorption sublayer **105** may pass through the outer conductive layer **103** and be reflected off of the interface between the outer conductive layer **103** and air due to the difference in the index of refraction at this interface. In either manner, photons may remain within the photovoltaic bristle passing back and forth through the absorption layer **111** until they are eventually absorbed or exit the bristle.

[0064] Each photovoltaic bristle **101** is made up of a core **106** that may be conductive or has a conductive outer surface, an absorption layer **111** and an outer conductive layer **103**, which will typically be a transparent conductive layer such as a transparent conductive oxide or transparent conductive nitride. Due to the cylindrical form of photovoltaic bristles, the absorption layer **111** surrounds the core **106**, and the outer conductive layer **103** surrounds the absorption layer **111**. Although, two absorber sublayers **104**, **105** are shown, it should be noted that the absorption layer **111** may include any number of absorber sublayers or regions of photovoltaically-active materials or combinations of photovoltaic materials. For example, the absorption layer **111** may include multiple absorber sublayers or regions that form a p-n junction, a p-i-n junction, or multi-junction regions, which have a generally circular cross-section as illustrated in FIG. **1A**. If the absorption layer **111** forms a p-i-n junction with three absorber sublayers, one sublayer may be the intrinsic portion forming the p-i-n junction. If the core **106** is a semiconductor core forming a p-n junction with a single absorber sublayer, the absorption layer **111** may include only one sublayer. Regardless of the number, the absorber sublayers or regions **104**, **105** may be made from one or more of silicon, amorphous silicon, polycrystalline silicon, single crystal silicon, cadmium telluride, gallium arsenide, aluminum gallium arsenide, cadmium sulfide, copper indium selenide, and copper indium gallium selenide.

[0065] The relative radial positions of the p-type, intrinsic, or n-type sublayers/regions may vary in different embodiments. For example, in one embodiment the p-type semiconductor material may be positioned radially inside the n-type semiconductor material. In another embodiment, the n-type semiconductor material may be positioned radially inside the p-type semiconductor material. In addition, multiple materials may be used to create a sequence of p-n and/or n-p junctions, or p-i-n junctions in the absorption layer. For example, the absorption layer may include an absorber sublayer of p-type cadmium telluride (CdTe) and an absorber sublayer of n-type cadmium sulfide (CdS). In an embodiment, the absorption layer **111** may be fully depleted. For example, the p-type region and the n-type region forming the sublayer or region **104** and the sublayer or region **105** may be fully depleted.

[0066] In an example embodiment, the absorption layer **111** may include a p-type semiconductor sublayer **105**, such as p-type cadmium telluride, and an n-type semiconductor sublayer of a different material, such as n-type-cadmium sulfide. In another example embodiment, one sublayer **104** may be a p-type region, such as p-type amorphous silicon, and another sublayer **105** may be an n-type region of the same material as the sublayer **104** but doped to form an n-type semiconductor, such as n-type amorphous silicon.

[0067] The outer conductive layer **103** has a radial thickness which may be measured radially from the outer surface of the absorption layer **111** to the outer surface of the outer conductive layer **103** (i.e., the outer surface of the photovoltaic bristle). In an embodiment, the outer conductive layer **103** is a transparent conductive oxide ("TCO"), such as a metal oxide. In an embodiment, the outer conductive layer **103** may include a dopant creating a p-type or n-type transparent conductive oxide. For example, the transparent conductive oxide layer **103** may be one of intrinsic zinc oxide, indium tin oxide, and cadmium tin oxide (Cd_2SnO_4). In an embodiment, the outer conductive layer **103** may include a transparent conductive nitride such as titanium nitride (TiN). In another embodiment, the outer conductive layer **103** may include a buffer with or without the dopant. Some examples of an outer conductive layer **103**, which may be a transparent conductive oxide with a dopant, include boron-doped zinc oxide, fluorine doped zinc oxide, gallium doped zinc oxide, and aluminum doped zinc oxide. Some examples of buffers that may be added to a transparent conductive oxide include zinc stannate (Zn_2SnO_4), titanium dioxide (TiO_2), and similar materials well known in the art.

[0068] Although not shown in FIGS. **1A-1B**, the outer conductive layer **103** may include any number of conductive and/or non-conductive sublayers to achieve a particular total optical thickness while simultaneously having a thin conductive sublayer. With multiple sublayers, the outer conductive layer **103** may also benefit from adding flexibility to the photovoltaic bristles for a more resilient photovoltaic bristle metamaterial device. The addition of a non-conductive sublayer may have refractive properties that improve off-angle photon absorption efficiency. Analysis and observations of prototypes indicate that outer conductive layers between 500 and 15,000 angstroms result in a decrease in electrical resistance in the conductive layers from field effects at the structural discontinuities in the photovoltaic bristles. However, the outer conductive layer **103** may need to be of a minimum optical thickness exceeding 500 and 15,000 angstroms a bristle to achieve the photon trapping and guiding effect shown in FIG. **1**A. Thus, the outer conductive layer **103** may include multiple layers to achieve the conflicting optical thickness requirement and the requirement for electrical resistivity benefits from field effects. As an example, the outer conductive layer **103** may have two sublayers including a conductive sublayer such TCO and a non-conductive sublayer such as an optically transparent polymer. As another example, the non-conductive sublayer may be a bi-layer including TCO and a polymer or glass. As a further example, the outer conductive layer **103** may include three sublayers where a non-conductive sublayer separates two conductive sublayers.

[0069] In an embodiment, the core **106** may be of a variety of conductive materials and non-conductive materials. In an embodiment, the core **106** may be a solid conductive core such as a metal. For example, the solid conductive core may be gold, copper, nickel, molybdenum, iron, aluminum, or silver. In an embodiment, the core **106** may include the same material as the substrate **202** (shown in FIG. **2**B). For example, the core **106** and the substrate **202** may include a polymer. In another embodiment, the core **106** may include a different material than the substrate **202**. In another embodiment, an inner conductive layer **107** may surround the core **106**. For example, the inner conductive layer **107** may be gold, copper, nickel, molybdenum, iron, aluminum, or silver to create a conductive core. In an embodiment, the core **106** may include a polymer with an inner conductive layer **107** surrounding the polymer. The inner conductive layer **107** may include similar material as the outer conductive layer **103**. For example, the inner conductive layer **107** may include a transparent conductive oxide, a transparent conductive nitride, and/or a non-conductive transparent material. The inner conductive layer **107** may include multiple layers (e.g., sublayers of TCO and a non-conductive optically transparent polymer) to achieve the conflicting benefits of field effects and proper optical depth for the photovoltaic device. In an embodiment, the core **106** may include a semiconductor material. For example, the core **106** may be made from one or more of silicon, amorphous silicon, polycrystalline silicon, single crystal silicon, cadmium telluride, gallium arsenide, aluminum gallium arsenide, cadmium sulfide, copper indium selenide, and copper indium gallium selenide.

[0070] FIG. **1**B also illustrates that photons striking the photovoltaic bristle **101** will have a higher probability of absorption when they strike the sidewall of a photovoltaic bristle at a compound angle that is less than 90 degrees but more the 0 degrees to the surface, where an angle perpendicular to the sidewall surface is considered to be 0 degrees. The compound incident angle includes a vertical plane component **133** (shown in FIG. **1**B) and a horizontal plane component **132** (shown in FIG. **1**A). The horizontal plane component **132** is defined by a photon **112** striking the outer surface of the bristle at a point along the perimeter of the circular cross-section plane forming an angle with the perimeter where an angle perpendicular to the perimeter is considered 0 degrees. Similarly, the vertical plane component **133** is defined by the photon **112** striking the outer surface of the bristle at a point along the height forming a vertical angle with the surface where an angle perpendicular to the surface is considered 0 degrees.

[0071] Analysis of photon absorption characteristics of the outer conductive layer have revealed that photons striking the surface of the sidewall of the photovoltaic bristle perpendicular to the horizontal component **132** and the vertical component **133** may result in a compound angle of 0 degrees and an increased probability of being reflected off the surface. Similarly, photons striking the surface of the sidewall of the photovoltaic bristle parallel to the vertical and the horizontal component will also have an increased probability of being reflected off the surface. However, photons striking the side surface at a compound angle between 10° and 80° have a high probability of being absorbed into the outer conductive layer **203**. Once absorbed, the internal refraction characteristics of the absorber sublayers **104**, **105** and outer conductive layer **103** cause the photons to remain within the photovoltaic bristle **101** for an extended time or path length. This characteristic is very different from conventional photovoltaic cells, which exhibit the maximum power conversion efficiency when the angle of incidence of photons is normal to its single planar surface.

[0072] The difference between the incident angle corresponding to conventional photovoltaic cells and the photovoltaic bristles is illustrated by angle θ_p in FIG. **1**B. The preferred incident angle for a traditional solar cell, θ_p, would form a right angle with the top of the bristle as well as the substrate of the full metamaterial device (not shown). Thus, not only does the photovoltaic bristle exhibit better absorption characteristics at off-angles (not perpendicular or parallel to the surface), the reference point for measuring an off-angle is different from that of a conventional photovoltaic cells. For a metamaterial device with photovoltaic bristles, the reference point is measured from the sidewall of a bristle in two planes, which is unachievable by a planar photovoltaic cell. Thus, due to the off-angle absorption characteristics of photovoltaic bristles, the embodiment photovoltaic cells exhibit significant power conversion efficiency across a broad range of angle of incidence. This translates to more power generation throughout the day than achievable from fixed solar panels with conventional planar solar arrays that produce their peak efficiencies (i.e., maximum power generation) when the sun is directly overhead.

[0073] FIG. **2**A illustrates a perspective view of metamaterial **200** comprising an array of photovoltaic bristles **201***a*, **201***b*, **201***c*, **201***d*, **201***e*, **201***f*, **201***g*, **201***h*, **201***i*, **201***j*, **201***k*, **201***l*, **201***m*, **201***n*, **201***o*, **201***p* extending from a flat substrate **202** (shown in FIG. **2**B). While illustrated with twelve photovoltaic bristles **201***a*-**201***p*, a metamaterial may include a larger number of photovoltaic bristles. The number of photovoltaic bristles **201** will depend upon the dimensions and spacing of the bristles and the size of the photovoltaic cell. As with conventional photovoltaic cells, metamaterials may be assembled together in large numbers to form panels (i.e., solar panels) of a size that are suitable for a variety of installations.

[0074] Each photovoltaic bristle **201***a*-**201***p* is characterized by its height "h," which is the distance that each bristle extends from the substrate **202**. Photovoltaic bristles **201***a*-**201***p* are also characterized by their radius "r". In an embodiment, all photovoltaic bristles **201***a*-**201***p* within an array will have approximately the same height h and approximately the same radius r in order to facilitate manufacturing. However, in other embodiments, photovoltaic bristles **201***a*-**201***p* within the array may be manufactured with different heights and diameters.

[0075] In an embodiment, the number of photovoltaic bristles in a photovoltaic cell may depend upon the substrate surface area available within the cell and the packing density or inter-bristle spacing. In an embodiment, photovoltaic bristles may be positioned on the substrate with a packing density or inter-bristle spacing that is determined based upon the bristle dimensions (i.e., h and r dimensions) as well as other parameters, and/or pattern variations. For example, a hexagonal pattern may be used rather than the trigonometric pattern shown in FIG. **2**A.

[0076] In the various embodiments, the dimensions and the inter-bristle spacing of photovoltaic bristles may be balanced against the shading of neighboring bristles. In other words, increasing the number of photovoltaic bristles on a plane may increase the surface area available for absorbing photons. However, each photovoltaic bristle casts a small shadow, so increasing the photovoltaic bristle density of a photovoltaic cell beyond a certain point may result in a significant portion of each bristle being shadowed by its neighbors. While such shadowing may not reduce the number of photons that are absorbed within the array, shadowing may decrease the number of photons that are absorbed by each photovoltaic bristle, and thus there may be a plateau in the photon absorption versus packing density of photovoltaic bristles.

[0077] A further consideration beyond shadowing is the wave interaction effects of the array of closely packed photovoltaic bristles. The interior-bristle spacing may be adjusted to increase the probability that photons entering the array are absorbed by the photovoltaic bristles' metamaterial properties considering the bulk material properties of the layered films that makeup the array. For example, specific characteristics such as extinction coefficient or absorption path length may predict an optimal dimensional design, although one may chose to deviate from this prediction resulting in a sacrifice in performance.

[0078] FIG. **2**B is a cross-sectional side view of a section of metamaterial **200** including photovoltaic bristles **201***m*, **201***n*, **201***o*, and **201***p* as illustrated in FIG. **2**A. As shown in FIG. **2**B the photovoltaic bristles extend from a substrate **202**. In an embodiment, the core **106** may be the same material as the substrate **202** and an inner conductive layer **107** may surround the core **106**. The absorber layer **111** may surround the inner conductive layer **107** and the outer conductive layer **103** may surround the absorber layer **111**. The absorber layer **111** may include any number of sublayer or regions. As illustrated in FIG. **2**B, the absorber layer **111** may include two sublayers or regions **104**, **105**. In an embodiment, the two absorber sublayers or regions **104**, **105** may be any semiconductor material where one sublayer or region is doped as n-type and the other is doped as p-type.

[0079] The metamaterial **200** may include a substrate **202** of any suitable substrate material known to one skilled in the art. For example, the substrate **202** may be glass, doped semiconductor, diamond, metal, a polymer, ceramics, or a variety of composite materials. The substrate **202** material may be used elsewhere in the metamaterial **200**, such as a material used in any layer of a photovoltaic bristle **201***m*-**201***n*. Alternatively, the material used in the substrate **202** may be different from other materials used in the photovoltaic bristles **201***m*-**201***n*. In an embodiment, the core **106** and the substrate **202** may include a common material. For example, the substrate **202** and the core **106** may include glass, semiconductor material, a polymer, ceramics, or composites. In a further embodiment, the core **106** and substrate **202** may include similar materials, while the inner conductive layer **107** is added over the substrate **202** and surrounding the core **106** creating a conductive core. The inner conductive layer **107** may include metal such as gold, copper, nickel, molybdenum, iron, aluminum, or silver. Alternatively, the inner conductive layer may include any of the materials used for the outer conductive layer **103** which may be used in combination with the previously listed metals.

[0080] In an embodiment, the inner conductive layer **107** may also be an inner refraction or reflection layer that is added on top of the core **106** in order to provide an inner reflection interface for photons. In this embodiment, a layer of semiconductive or insulator material, such as B:ZnO, Al:ZnO, ZnO, or ITO, may be applied over the metal core. This layer may be at least one-half wavelength in thickness, depending on the refractive index of the material. For example, such a layer made of Al:ZnO (AZO) may be approximately 500 to 1500 angstroms thick over which the absorber layer may be applied. Such an AZO layer has a refractive index that is lower than the absorber layer. This difference in refractive index coupled with the curvature of the interface of these two layers will reflect the photons before they reach the metal core. The reflection induced by this design may exhibit lower losses than the designs in which photons reflect from a metal surface of the core. The use of such a refraction layer may be included in any of the embodiments illustrated and described herein. For example, in the embodiments in which the center of the core is a plastic rod, a metal layer is applied over the plastic core and then the AZO is applied over the metal layer. In further embodiments, this refractive layer forming a reflecting interface may be formed using multiple layers, such as: ITO-AZO; ITO-AZO—ITO; TiO2-TiN—TiO2; ZnO-AZO—ZnO; etc. Such multiple layers may function similar to a Bragg reflector used in fiber optics.

[0081] In ordering reason the percentage of solar photons striking photovoltaic bristles at the appropriate angle of incidence, one embodiment orients the photovoltaic bristles at an angle on a corrugated substrate. Positioning photovoltaic bristles at an angle to incident light increases the probability of off-axis photon absorption, which may reflect and propagate photons around and within the photovoltaic bristles, thereby developing an equilibrium standing wave and increasing probability of converting photon energy into electrical energy. Consequently, embodiment photovoltaic cells with such a corrugated shape may generate more electrical power than is possible from conventional photovoltaic cells.

[0082] In addition to increasing the probability of photon absorption, embodiment corrugated photovoltaic cells provide more surfaces and more photovoltaic bristles for photon absorption within a given planar footprint than a comparable flat substrate configuration. Each corrugated photovoltaic cell may include a large number of angled surfaces with photovoltaic bristles, compared to a conventional flat substrate photovoltaic cell that has only a single flat surface or absorbing photons. The improvements from the corrugated photovoltaic cell results in an increase in optical volume enabling more photon absorption and power generation from such a metamaterial device.

[0083] FIG. 3A is a perspective view of an embodiment metamaterial **300** comprising a corrugated shaped substrate **302** (shown in FIG. 3B) with arrays of photovoltaic bristles **301** positioned on each slanted substrate surface **308***a*, **308***b*, **308***c*, **309***a*, **309***b*, and **309***c*. Although FIG. **3**A depicts six slanted substrate surfaces, in an embodiment, the metamaterial **300** may have a larger number of slanted substrate surfaces. In FIG. **3**A, each slanted substrate surface **308***a*-**308***c*, and **309***a*-**309***c* may form an angle θ_b with the flat foundation **303** of the substrate **302**. In an embodiment angle θ_b may be between about 30 and about 60 degrees. In further embodiments the angle θ_b may be 30-35 degrees, 35-40 degrees, 40-45 degrees, 45-50 degrees, 50-55 degrees, and 55-60 degrees. In an embodiment, arrays of photovoltaic bristles **301** may be oriented so that their long axis is normal to the slanted substrate surfaces **308***a*-**308***c* and **309***a*-**309***c* including angle θ_b to increase the probability of photon absorption and photon trapping and guiding from photons striking the sidewalls of each photovoltaic bristles **301** at compound angles approximately between 10 and 80. It should be noted that each slanted substrate surface **308***a*-**308***c* and **309***a*-**309***c* may include any number of photovoltaic bristles **301** (i.e. more than the twelve photovoltaic bristles **301** shown in the figure).

[0084] FIG. 3B is a cross-sectional side view of a section of a metamaterial **300** comprising slanted substrate surfaces **308***a* and **309***a* at angles θ_b with the foundation **303** and an array of photovoltaic bristles **301** on each slanted substrate surface. As described above, each photovoltaic bristle **301** may include a core **106**, an inner conductive layer **107**, and an absorber layer **111** with absorber sublayers **104**, **105** surrounding the inner conductive layer, and an outer conductive layer **103** surrounding the absorber layer **111**. In an embodiment, the core **106** may be the same material as the substrate **302**. The photovoltaic bristles **301** extend from the corrugated surface **302** perpendicular to each slanted surface **308**, **309**. As illustrated in the figure, this angle enables photons **112** traveling along the photon path **113** to enter the sidewall of the photovoltaic bristle **301** at a compound angle of approximately 10-80°.

[0085] In another embodiment, photovoltaic bristles are position only on alternating slanted surfaces of the corrugated substrate, with the opposite surfaces lacking such structures. This embodiment configuration may reduce manufacturing costs while presenting photovoltaic bristles on the services most likely to receive solar radiation when deployed. Additionally, the slanted surfaces that do not include photovoltaic bristles may be coated with a reflective material (e.g., a metal) so that photons striking that surface are reflected at a desirable angle into the photovoltaic bristles on the opposite surface. Such an embodiment is illustrated in FIGS. **4**A and **4**B.

[0086] FIG. 4A is a perspective view of metamaterial **400** comprising a corrugated shaped substrate **402** (shown in FIG. 4B) and arrays of photovoltaic bristles **401** positioned at normal from the planes of alternating slanted substrate surfaces **408***a*, **408***b*, and **408***c*. In an embodiment, slanted substrate surfaces **409***a*, **409***b*, and **409***c* may be without arrays of photovoltaic bristles **401** and may be configured with a reflective surface coating, such as a metal, that may reflect photons into the photovoltaic bristles on the opposite surface is illustrated in FIG. 4B. Although FIG. **4**A depicts six slanted substrate surfaces, in an embodiment, the metamaterial **400** may have a larger or smaller number of slanted substrate surfaces.

[0087] FIG. 4B is a cross-sectional side view of a section of metamaterial **400** with a corrugated substrate **402** comprising slanted substrate surfaces **408***a*, **408***b*, **409***a*, **409***b* at angles 1N with the foundation **403**. In an embodiment, each slanted substrate surface **408***a*, **408***b* may include an array of photovoltaic bristles **401** configured approximately normal to the slanted substrate surface. In an embodiment, slanted substrate surfaces **409***a* and **409***b* may include a reflective layer **405**. As such, the reflective layer **405** may reflect photons **411** along a photon path **412** so that the reflected photons **411'** strikes the photovoltaic bristles extending from the adjacent slanted substrate surface **408***b* of the substrate **402**. In embodiment, a reflective layer **405** (i.e., reflective film) may be any material that has high reflective characteristics to reflect photons usable for the embodied metamaterial.

[0088] FIG. **5** illustrates an advantage of the various embodiment photovoltaic cells when installed on a typical structure **502** (e.g., a house) having a roof with angled surfaces **504**, **506**. In this illustrative figuration, photovoltaic cells **200** on a northern facing roof surface may have a flat profile and feature photovoltaic bristles **201** that extend perpendicular from the surface. Since this surface of the roof **506** receives sunlight at an angle, the incident sunlight on this surface is preferable for increasing photon absorption on such a photovoltaic cell **200**. On the southern facing roof surface **504**, corrugated photovoltaic cells **300**, **400** may be used since the sunlight will be striking the roof surface **504** at closer to a perpendicular angle of incidence. The **301**, **304** angular orientation of the photovoltaic bristles on such corrugated photovoltaic cells **300**, **400** ensures that incident sunlight strikes the photovoltaic bristles at angles of incidence that will increase photon absorption.

[0089] Various embodiment methods of making photovoltaic bristles are now presented.

[0090] An embodiment method **800** for manufacturing photovoltaic bristles using a press or stamping process is illustrated in FIGS. **6**A-**6**H, **7**A-**7**C, FIG. **8**. This embodiment method **800** may enable fabricating photovoltaic bristles using low-cost substrate materials such as plastics and polymers that may be processed rapidly in large volumes. This embodiment method will be described with reference to FIGS. **6**A-**6**H and FIG. **8** together. Although the figures illustrate and the text describes a rod imprint design, a via design may be similarly created as shown and described with reference to method **1600**. Additionally, any of a variety of raised shapes other than cylindrical rods or cones may be produced on the substrate using the embodiment methods and embodiment imprinting systems, including ridges, a mesh of interlocking ridges; hemispheres, etc.

[0091] In method **800** in block **804**, a plastic or polymer block or starting material may be processed in order to prepare it for a pressing or forming operation. The methods used for preparing such a polymer for pressing will depend upon the type of plastic or polymer selected. As illustrated in FIGS. **6**A and **6**B, in block **808** a die or mold **602** including a number of bristle holes **604** for forming the bristle cores may be pressed into the plastic or polymer material **202** and then removed, thereby forming an array of cores **106** out of the plastic polymer **202**. In an embodiment, vertical stamp **602** moves in a downward vertical manner into a polymer substrate **202** forming cores **106** and moving vertically away from the substrate **202** and the formed cores **106**. Alternatively, a rolling press or rolling die may be applied to a moving sheet or tray of material similar to printing press techniques.

[0092] When using a rolling press or rolling die a separate roll-to-web and web-to-plate sub-process may create the associated rolling stamps and the array of cores on the substrate for use in method **800**. The sub-process is discussed in depth later in this application with reference to FIGS. **33**A-**33**G, **34**, **35**A-**35**E, **36**A-**36**E. Generally, a master template is created using photolithographic techniques or nanoimprint lithography. The master template imprints a pattern on a polymer sheet or a web. The sheet or web may be a base material with a thin polymer imprintable layer or coating. For example, the sheet could be glass and/or the web could be polyester. The web is then used in combination with rollers (e.g., a rolling stamp) to stamp cores on a substrate similar to substrate **202** with cores **106** illustrated in FIG. **6**B.

[0093] In block **810**, the newly formed array of cores **106** may be cured or otherwise processed in order to improve the material properties, such as to harden the material. This may involve processing with heat, ultraviolet radiation, and/or chemical vapor exposure, as would be well-known in the polymer arts and depend upon the type of material used. In an embodiment, the material processing in block **810** may be accomplished as part of the stamping operation in block **808**, partly as part of the stamping operation and as a host stamping process, or entirely as a post-stamping process. For example, a rolling stamp may include an ultraviolet light that is configured so that when the rolling stamp rotates over the unformed substrate **202** the ultraviolet light simultaneously cures or partially cures the newly formed cores **106**.

[0094] As illustrated in FIG. **6**C, in block **812**, and inner conductive layer **107** may be formed over the cores **106**. This may be accomplished by chemical vapor deposition, plasma enhanced chemical vapor deposition, physical deposition, plasma deposition, sputtering techniques, or electro-deposition techniques. The inner conductive layer **107** may further be formed or thickened by electroplating processes. Multiple conductive layers may be applied as part of block **812**. In an embodiment, the inner conductive layer or layers may be one or more of copper, aluminum, gold, nickel, titanium, silver, tin, tantalum, and chromium, as well as alloys of such metals. This process forms an inner conducting core for the photovoltaic bristle.

[0095] To form the photovoltaic portion of the photovoltaic bristles, a number of semiconductor layers may be applied to the inner conducting core using well-known semiconductor processing methods. As illustrated in FIG. **6**D, in block **804**, a first absorber layer of semiconductor material may be formed over the inner conductive layer. For example, the first absorber layer **105** may include silicon, amorphous silicon, polycrystalline silicon, single crystal silicon, cadmium telluride, cadmium sulfide, gallium arsenide, copper indium selenide, and copper indium gallium selenide. The first absorber layer **105** over the inner conductive layer **107** by electroplating, chemical vapor deposition, atomic layer deposition, etc.

[0096] As illustrated in FIG. **6**E, in block **842** a second semiconductor material layer may be formed over the first absorber layer, with the first and second absorber layers having material properties to create a p-n junction or n-p junction configured to release electrons upon absorbing a photon. Any deposition method used to add the first absorber layer **105** may also be used to add the second absorber layer **104**. In an embodiment, the deposition method for the second absorber layer **104** may be the same deposition method used for adding the first absorber layer **105**. In an embodiment, the second absorber layer **104** may include a semiconductor material. For example, the second absorber layer **104** may include silicon, amorphous silicon, polycrystalline silicon, single crystal silicon, cadmium telluride, cadmium sulfide, gallium arsenide, copper indium selenide, and copper indium gallium selenide. In an embodiment, the second absorber layer **104** may be an absorber sublayer or region comprising the same material as the first absorber layer **105** with a different dopant. For example, the first absorber layer **105** may be p-doped amorphous silicon and the second absorber layer **104** may be n-doped amorphous silicon. In an embodiment, the second absorber layer **104** may be an absorber sublayer comprising a different material as the first absorber layer **105**. For example, the first absorber layer **105** may be p-doped cadmium telluride and the second absorber layer **104** may be n-doped cadmium sulfide. In optional block **846**, additional absorber layers of semiconductor materials may be applied to form multiple p-n and/or n-p junctions (e.g., n-p-n or p-n-p junctions).

[0097] With the photon absorber layers formed, an outer conductive layer may be formed in block **848** as illustrated in FIG. **6**G. The outer conductive layer may be a transparent conducting oxide or transparent conducting nitride, as are well-known in the photovoltaic technologies. In an embodiment, the only two absorber layers **104**, **105** may be applied, and thus the outer conductive layer **103** is deposited (e.g., by chemical deposition or physical deposition) over the last absorber layer **104** as shown in FIG. **6**F. In optional block **852**, additional outer conductive layers may be applied depending upon the configuration of the photovoltaic bristles. Although the outer conductive layer in FIG. **6**G includes two layers, any number of layers may make up the outer conductive layer **103**.

[0098] Corrugated photovoltaic cells may also be configured using similar processes as illustrated in FIGS. **7**A-**7**C. For example, as illustrated in these figures, the operations of forming an array of cores in the plastic or polymer in block **808** may be accomplished by alternately pressing the material **302** with dies that are oriented at the desired angle of the corrugated surfaces. For example, photovoltaic bristles **106** may be formed on corrugated surfaces in the 1st orientation by pressing the material with dies **702** long one angle as illustrated in FIG. **7**B, followed by pressing the opposite surfaces with opposite oriented dies **702** as illustrated in FIG. **7**C.

[0099] To form the embodiment illustrated in FIG. **4**C in which photovoltaic bristles are formed on only alternating sides of the corrugated surface, only a single pressing step as illustrated in FIG. **7**B may be a comp push. In some embodiments, in optional block **854** a reflective layer may be applied to the surfaces that do not feature photovoltaic bristles. This may be accomplished using photoelectric graphic methods, such as coding the photovoltaic bristles with a photoresist that is removed from the other surfaces before a reflective layers applied.

[0100] As illustrated in FIG. **6**H, in optional block **856** but conductive traces may be added to portions of the solar cells to gather and distribute electricity from the photovoltaic bristles, thereby reducing the path length of electrons through the transparent conducting oxide layers. Finally in optional block **858**, a transparent coating may be applied over the bristles in order to provide desirable strength and photon absorption c characteristics. For example, a transparent coating **608** may seal each bristle in a transparent material providing stability to each bristle to prevent the bristles from breaking. The transparent coating **608** may be conventional shatterproof material such as ethylene-vinyl acetate (EVA).

[0101] In a further embodiment method that uses some of the same processes as in method **800**, the material forming the cores **106** may be poured and formed in a mold **612** instead of being pressed, as illustrated in FIGS. **6**I through **6**K. As illustrated in FIG. **6**I, instead of a die **602**, the same basic shape may be inverted to form a mold **612** onto which may be poured the material **614** to form the cores and supporting substrate. This material **614** may be a plastic or polymer, but may also be other materials, such as a metal, a ceramic paste, or a liquid glass (e.g., common glass). In this embodiment, the operations of forming the array of cores in block **808** include pouring the base material **614** into the mold **612**, sufficiently covering the mold surface to provide a substrate **202** as shown in FIG. **6**J. The material may be cured in block **810** in this state before the mold **612** is removed as shown in FIG. **6**K. Thereafter, the operations of depositing absorber layers and outer conductive layers may be accomplished as described above with reference to blocks **812**-**858**.

[0102] Another embodiment method for forming an array of bristles for a metamaterial device involves a plating up metal cores using a photolithographic methods to create a template on a substrate. The plating up method is illustrated in FIGS. **9**A-**9**J and FIG. **10**. In block **1008** a metal layer may be deposited over a substrate. As illustrated in FIG. **9**A the metal layer **187** may be deposited directly may be deposited over the substrate **202** by chemical deposition or physical deposition. In block **1010** a photoresist layer over the metal layer. The photoresist layer **189** may be deposited over the metal layer **187** by chemical vapor deposition or physical deposition as shown in FIG. **9**A. The photoresist layer **189** may be a positive photoresist or a negative photoresist.

[0103] In block **1012** a mask may be applied over the photoresist. As shown in FIG. **9**B, the mask **195** may include holes **195***a* through which ultraviolet light may pass so that only the photoresist beneath the holes is exposed as shown in FIG. **9**B. In block **1014** the photoresist layer may be exposed an ultraviolet light through the mask to create exposed photoresist portions **189***a* as shown in FIG. **9**B. When a positive photoresist is used, the exposed photoresist portions **189***a* match the mask holes **195***a*. However, if a negative photoresist is used, ultraviolet light may be able to pass through the entire mask except through solid portions of the mask which block the ultraviolet light. Regardless, after the ultraviolet light is applied to the photoresist **189** creating exposed portions **189***a*, the mask **195** is removed leaving the entire photoresist layer **189**.

[0104] In block **1016** the method may include developing the photoresist layer to create a template of masked portions. A developer may be used to dissolve only the exposed portions of the photoresist. Assuming the method uses a positive photoresist **189**, the exposed photoresist portions **189***a* are removed creating voids **189***b* in the photoresist layer that extend to the metal layer **187** as shown in FIG. **9**C. These voids **189***a* along with the remaining photoresist layer **189** form a template over the metal layer **187**.

[0105] In block **1018** additional metal may be added to the metal layer through the photoresist layer using electroplating, chemical vapor deposition or plasma deposition methods, forming metal cores. As shown in FIG. **9**D the metal cores **106** may fill the voids **189***b* within the photoresist **189** by electroplating metal in the voids **189***b*. Metal cores may also extend above the photoresist layer. Alternatively, a second metal layer may fill the voids **189***b* and covers the remaining portions of the photoresist layer **189** (not shown). The metal cores **106** may be the same material as the metal layer **187** such as gold, copper, nickel, molybdenum, iron, aluminum, or silver, or an alloy of the same.

[0106] In block **1020** the photoresist layer may be removed using conventional methods. As shown in FIGS. **9**D and **9**E, the metal cores **106** may only fill the voids **189***b* created by the exposed photoresist layer through an electroplating process. When the photoresist layer **189** is removed, only the formed metal cores **106** (within voids **189***b*) remain. Alternatively, if a second metal layer fills the voids **189***b* and covers the photoresist layer **189**, a lift-off process known in the art may remove the photoresist layer **189** and the second metal layer leaving only the metal cores **106**. The resulting metal cores **106** from the lift-off process may have height greater than the voids **189***b*.

[0107] In block **1040** a first absorber layer (i.e., sublayer) **105** may be deposited over the metal core **106** for metamaterials **200** illustrated in FIG. **9**F. In an embodiment, the first absorber layer **105** may include a semiconductor material. For example, the first absorber layer **105** may include silicon, amorphous silicon, polycrystalline silicon, single crystal silicon, cadmium telluride, cadmium sulfide, gallium arsenide, copper indium selenide, and copper indium gallium selenide. In an embodiment, the first absorber layer **105** may be deposited over the metal core **106** by electroplating, chemical vapor deposition, atomic layer deposition, etc. In an embodiment, the first absorber layer **105** may be deposited over the inner conductive layer **107** by sputtering, electron beam, pulsed laser deposition, etc.

[0108] In block **1042** a second absorber layer **104** may be deposited over the first absorber layer **105** for metamaterial **200** as illustrated in FIG. **9**G. Any deposition method used with respect to the first absorber layer **105** may also be used with the second absorber layer **104**. In an embodiment, the second absorber layer **104** may include silicon, amorphous silicon, polycrystalline silicon, single crystal silicon, cadmium telluride, cadmium sulfide, gallium arsenide, copper indium selenide, and copper indium gallium selenide. In an embodiment, the second absorber layer **104** may be an absorber sublayer or region comprising the same material as the first absorber layer **105** with a different dopant. For example, the first absorber layer **105** may be p-doped amorphous silicon and the second absorber layer **104** may be n-doped amorphous silicon. In an embodiment, the second absorber layer **104** may be an absorber sublayer comprising a different material as the first absorber layer **105**. For example, the first absorber layer **105** may be p-doped cadmium telluride and the second absorber layer **104** may be n-doped cadmium sulfide.

[0109] In some implementation multiple absorber layers may be applied. So, in optional block **1046** one, two or more additional absorber layers may be applied over the previous layer in a manner similar to the process steps in blocks **1040** and **1042**. As shown in FIG. **9**H, in block **1048**, an outer conductive layer **103** may be deposited over the last absorber layer (e.g., second absorber layer **104**), such as by chemical deposition or physical deposition.

[0110] As illustrated in FIG. **9**I, additional outer conductive layers may be applied in optional block **1052**. In an embodiment, the outer conductive layers may comprise a transparent non-conductive layer **103***a* (e.g., an optical transparent polymer) and a conductive layer **103***b* (e.g., a transparent conducting oxide). Although the outer conductive layer shown in FIG. **9**I includes two layers, any number of layers may make up the outer conductive layer **103**. The non-conductive layer **103***a* illustrated in FIG. **9**I may be a conformal layer which may act as a protective coating similar to the transparent coating **608** described below. The conformal non-conductive layer **103***a* may be added by dip coating, chemical vapor deposition, physical deposition, and atomic layer deposition, and evaporation techniques.

[0111] In optional block **1056** current conducting traces may be added to the metamaterials **200** and **300**. As explained later with reference to FIGS. **23** and **25**, the current conducting traces may be added by creating a template using photolithography and depositing a highly conductive material in a selected position from the template. The current conducting trace may be deposited on the metamaterial by any known deposition method such as chemical vapor deposition, physical deposition, plating, or ink jet material deposition. The ink jet deposition methods may utilize piezoelectric ink jets to add silver or other colloidal conductive material to the desired position without damaging the metamaterial.

[0112] Alternatively, the current conductive traces may be added by etching with laser ablation in combination with a deposition method such as ink jet. Tuned wavelength lasers may etch desired layers by controlling the laser's wavelength for different layers within the metamaterial. Once etching is complete, the method may include adding the electrical connections such as the current conducting traces at the desired positions on the metamaterial by chemical vapor deposition, physical deposition, plating or inkjet deposition.

[0113] As a further alternative, the metamaterial may be etched using ink jet technology to apply an acid to precise locations followed by applying the conductive material using the same technology, or any other deposition method known in the art.

[0114] Regardless of method used, the current conducting traces may allow for efficient transfer of electricity by adding a lower resistant electrical path within the metamaterials.

[0115] In optional block **1058** a transparent coating may be deposited over the bristles. As illustrated in FIG. **9**J, the transparent coating **608** is different from the outer conductive layer **103** and its sublayers **103***a* and **103***b*. The transparent coating **608** may fully fill the voids between each bristle and extending beyond the height of each bristle. As shown, the transparent coating **608** may not be conformal thus leading to deposition methods that use liquid solutions. Thus, the method of depositing transparent coating **608** may include one or more of the following immersion coating, spray gel techniques, extrusion techniques, a spreader bar, photoresist techniques, sol gel techniques, or any other methods known in the art. The transparent coating **608** may seal each bristle providing stability and to prevent them from breaking as well as insulate each bristle from any heat created by the metamaterial device. Observations and experimentations also indicate enhanced peak power generation as the sun translates across the sky for a metamaterial device with a transparent coating **608** having a index of refraction similar to glass (e.g., around 1.5). All these benefits may add enhanced power performance and total power generation of the metamaterial device.

[0116] A further method for forming an array of bristles for metamaterial **200** includes forming bristles by etching vias in a substrate through a photolithographic template. The method includes adding an inner conductive layer **107** and a base layer **202***b* over the original substrate **202***a* and in the vias. The method then includes turning the metamaterial device over and depositing absorber layers **104**, **105**, outer conductive layers **103***a*, **103***b* and a transparent coating over the inner conductive layer. This via method is illustrated in FIGS. **11**A-**11**L and FIG. **12**.

[0117] In block **1210** a photoresist layer may be deposited over the substrate. The photoresist layer **189** may be deposited over the substrate **202***a* by chemical vapor deposition or physical deposition as shown in FIG. **11**A. Although FIGS. **11**B-**11**D illustrates a positive photoresist, the photoresist layer **189** may be negative photoresist.

[0118] In block **1212** a mask may be deposited over the photoresist layer. The mask **195** may be any suitable mask known in the art. As shown in FIG. **12**B, the mask **195** may include mask holes **195***a*. Alternatively, if using a negative photoresist, the pores **195***a* may be filters for blocking ultraviolet light.

[0119] In block **1214** the method may include exposing an ultraviolet light to the photoresist layer through the mask. The ultraviolet light from the ultraviolet light source **193** passes through the mask holes **195***a* into the photoresist layer **189** creating exposed portions **189***a* of the photoresist layer as shown in FIG. **11**B. The exposed photoresist portions **189***a* match the mask holes **195***a*. However, if a negative photoresist is used, ultraviolet light may be able to pass through the entire mask except through filters where at the locations of mask holes **195***a*, which block the ultraviolet light. Regardless, after the ultraviolet light is applied to the photoresist layer **189** creating exposed portions **189***a*, the mask **195** is removed leaving the entire photoresist **189**.

[0120] In block **1216** the method may include developing the photoresist layer to create a template, such as by using developer to dissolve the exposed portions of the photoresist as shown in FIG. **11**C. After dissolving the required portions of the photoresist layer, the remaining photoresist layer **189** portions forms a template over the substrate **202***a*.

[0121] In block **1218** the substrate may be etched through the template creating vias. Etching may include wet etching or dry etching Regardless of the etching technique, vias **1103** are formed from within the substrate **202***a*.

[0122] In block **1220** the photoresist layer may be removed as shown in FIGS. **11**D-**11**E, leaving only the original substrate **202***a* with formed vias **1103**. Any process known in the art may remove the photoresist layer **189** from the substrate. For example, the photoresist may be removed by stripping or dissolving the remaining portion of the photoresist.

[0123] In block **1222** an inner conductive layer may be deposited in the vias. As shown in FIG. **11**F, the inner conductive layer **107** may be deposited as a layer that covers the bottoms and the sides of the vias **1103** as well as covering the top of the substrate **202***a*. Although the method steps do not explicitly show it, the inner conductive layer **107** may include multiple layers similar to the outer conductive layer **103** later described with reference to blocks **1248**, **1450**, and **1452**.

[0124] As shown in FIG. **11**G, in block **1224** the base layer may be deposited over the inner conductive layer **107**. Although the base layer **202***b* is a separate layer than the original substrate **202***a*, it may be the same material as the original substrate **202***a*. Alternatively, the base layer **202***b* may be a different substance. It should be noted, that although FIG. **11**G illustrates the base layer **202***b* completely fills the vias **1103**, the base layer may **202***b* may only partially fill the vias **1103** and may be deposited similar to the inner conductive layer **107** resulting in an unfilled void and a non-solid core.

[0125] In block **1226** the device may be turned over, and the substrate etched in block **1228**. FIG. **11**H illustrates the metamaterial device turned over (i.e., flipped 180 degrees) as well as the original substrate etched away leaving the inner conductive layer **107** and the base layer **202***b*. A wet etching process (i.e., using acid) or a dry etching process may remove the original substrate **202***a* resulting.

[0126] In block **1240** the method may be depositing a first absorber layer. The first absorber layer (i.e., sublayer) **105** may be deposited over the inner conductive layer **107** for metamaterial **200** as illustrated in FIG. **11**I. In an embodiment, the first absorber layer **105** may include a semiconductor material. For example, the first absorber layer **105** may include silicon, amorphous silicon, polycrystalline silicon, single crystal silicon, cadmium telluride, cadmium sulfide, gallium arsenide, copper indium selenide, and copper indium gallium selenide. In an embodiment, the manufacturing system may add the first absorber layer **105** over the metal core **106** by electroplating, chemical vapor deposition, atomic layer deposition, etc. In an embodiment, the manufacturing system may add the first absorber layer **105** over the inner conductive layer **107** by sputtering, electron beam physical deposition, pulsed laser deposition, etc.

[0127] In block **1242** a second absorber layer may be deposited over the first absorber layer **105** for metamaterial **200** as illustrated in FIG. **11**I. Any deposition method used to deposit the first absorber layer **105** may be used to deposit the second absorber layer **104**. In an embodiment, the deposition method for the second absorber layer **104** may be the same deposition method used for adding the first absorber layer **105**. In an embodiment, the second absorber layer **104** may include a semiconductor material. For example, the second absorber layer **104** may include silicon, amorphous silicon, polycrystalline silicon, single crystal silicon, cadmium telluride, cadmium sulfide, gallium arsenide, copper indium selenide, and copper indium gallium selenide. In an embodiment, the second absorber layer **104** may be an absorber sublayer or region comprising the same material as the first absorber layer **105** with a different dopant. For example, the first absorber layer **105** may be p-doped amorphous silicon and the second absorber layer **104** may be n-doped amorphous silicon. In an embodiment, the second absorber layer **104** may be an absorber sublayer comprising a different material as the first absorber layer **105**. For example, the first absorber layer **105** may be p-doped cadmium telluride and the second absorber layer **104** may be n-doped cadmium sulfide.

[0128] As mentioned above, in some implementations multiple absorber layers may be applied, so in optional block **1246** such additional absorber layers may be over the previous layer in a manner similar to the process steps in blocks **1240** and **1242**. As shown in FIG. **11**J, in block **1248**, an outer conductive layer **103** may be deposited over the last absorber layer (e.g., second absorber layer **104**). In optional block **1252**, multiple outer conductive layers may be applied as illustrated in FIG. **11**K. As discussed above, such outer conductive layers may be applied using chemical deposition or physical deposition.

[0129] In optional block **1256** current conducting traces may be deposited on the metamaterials **200**. As explained later with reference to FIGS. **23** and **25**, the current conducting traces may be added by creating a template using photolithography and depositing a highly conductive material in a selected position from the template. The current conducting traces may be deposited on the metamaterial by any known deposition method such as chemical vapor deposition, physical deposition, plating, or ink jet material deposition. The ink jet deposition may utilize piezoelectric technology and add silver or any other colloidal material to the desired position without damaging the metamaterial. Alternatively, the current conductive traces may be added by etching with laser ablation in combination with a deposition method such as ink jet techniques. Tuned wavelength lasers may etch desired layers by controlling the laser's wavelength for different layers within the metamaterial. Once etching is complete, the method may include adding the electrical connections such as the current conducting traces at the desired positions on the metamaterial by chemical vapor deposition, physical deposition, plating or inkjet deposition. As a further alternative, the metamaterial may be etched by ink jet technology using acid followed by deposition of conductive material using the same technology or any other deposition method known in the art. Regardless of method used, the current conducting traces may allow for efficient transfer of electricity by adding a lower resistant electrical path within the metamaterials.

[0130] As illustrated in FIG. **11**L, in optional block **1258** a transparent coating may be applied over the bristles. Such a transparent coating **608** may be different from the outer conductive layer **103** and any sublayers **103***a* and **103***b*. The transparent coating **608** may fully fill the voids between each bristle and extend beyond the height of each bristle. As shown, the transparent coating **608** may not be conformal thus leading to deposition methods that use liquid solutions. Thus, the method of depositing transparent coating **608** may include using one or more of the following immersion coating, spray gel techniques, extrusion techniques, a spreader bar, photoresist techniques, sol gel techniques, or any other methods known in the art. In an embodiment, the transparent coating **608** may be a shatterproof material such as EVA. The transparent coating **608** may seal each bristle providing stability and to prevent them from breaking as well as insulate each bristle from any heat created by the metamaterial device. Observations and experimentations also indicate enhanced peak power generation as the sun translates across the sky for a metamaterial device with a transparent coating **608** having a index of refraction similar to glass (e.g., around 1.5). All these benefits may add enhanced power performance and total power generation of the metamaterial device.

[0131] A further method for forming an array of bristles for a metamaterial **200** includes forming the bristles by etching vias in a substrate through a photolithographic template. Bristles are formed within the vias by depositing an outer conductive layer, absorber layers, an inner conductive layer, an optional base layer. After forming the bristles, the metamaterial may be turned over where the original substrate is left intact serving as a protective coating and an optical enhancement for the metamaterial **200**. This via method is illustrated in FIGS. **13**A-**13**L and FIG. **14**. As shown in FIGS. **13**A-**13**L and the method steps in FIG. **14**, an etching technique may be used to create vias, which is particularly useful when using a glass substrate.

[0132] In block **1410** a photoresist may be deposited over the substrate. The photoresist layer **189** may be deposited over the substrate **202***a* by spin on, spray on, or other controlled flow methods know in the art as shown in FIG. **13**A. Although FIGS. **13**B-**13**D illustrate a positive photoresist, the photoresist layer **189** may be negative photoresist.

[0133] In block **1412** a mask may be positioned over the photoresist layer. The mask **195** may be any suitable mask known in the art. As shown in FIG. **12**B, the mask **195** may include mask holes **195***a*. Alternatively, if using a negative photoresist, the pores **195***a* may be filters for blocking ultraviolet light.

[0134] In block **1414** the method may include exposing an ultraviolet light to the photoresist layer through the mask. The mask **195** may be any suitable mask known in the art. As shown in FIG. **13**B, the mask **195** may include mask holes **195***a*.

[0135] In block **1416** the method may include developing the photoresist layer to dissolve the exposed portions of the photoresist layer. Assuming a positive photoresist layer **189**, the exposed portions **189***a* are removed creating voids **189***b* in the photoresist layer that extend to the substrate **202***a* as shown in FIG. **13**C. After dissolving the required portions of the photoresist layer **189**, the remaining photoresist layer **189** forms a template over the substrate **192**.

[0136] In block **1418** the substrate may be etched through the template creating vias. Etching may include wet etching or dry etching Regardless of the etching technique employed, vias **1103** are formed from within the substrate **192**.

[0137] In block **1420** the photoresist layer may be removed leaving the substrate **192** with formed vias **1103** as shown in FIGS. **13**D-**13**E.

[0138] Since the outside layers of the photovoltaic bristles are laid down first, conductive traces used to draw current from the photovoltaic cells may be laid down as a first step. Thus, in optional block **1421**, conductive traces may be applied to the substrate. Vias for such conductive traces may be formed as part of the operations in blocks **1410**-**1420**. Alternatively, conductive traces may be applied to the substrate using dedicated photolithography steps, laser ablation steps, and deposition steps such as those described above and below. In a particular embodiment, the conductive traces may be applied using spray jet techniques. In block **1422** an outer conductive layer may be deposited in the vias, such as by chemical vapor deposition or physical deposition. If conductive traces are prior to the outer conductive layer, the method may include depositing the outer conductive layer **103** over the conductive traces as a conformal film.

[0139] Although not shown in FIGS. **13**A-**13**L, the metamaterial may include an outer conductive layer **103** with multiple sublayers. So, in optional block **1452** another outer conductive layer may be applied over the previous layer, essentially repeating blocks **1450** and **1452**. As shown in FIGS. **13**G-**13**H, in block **1440** a first absorber layer may be deposited on the outer conductive layer(s), and in block **1442** a second absorber layer may be deposited over the first absorber layer. The first and second absorber layer **104**, **105** may be applied by chemical vapor deposition.

[0140] In block **1446** additional absorber layer applied over the previous layer in a manner similar to the process steps in blocks **1440** and **1442**. In block **1448**, an inner conductive layer **107** may be applied over the last absorber layer (e.g., second absorber layer **105**). In an embodiment, the method may include adding only two absorber layers **104**, **105** and thus the inner conductive layer **107** is deposited over the last absorber layer **105** by chemical deposition or physical deposition as shown in FIG. **13**I. Although the method steps do not explicitly show it, the inner conductive layer **107** may also include multiple layers similar to the outer conductive layer **103**.

[0141] In block **1424** a base layer may be deposited. As shown in FIG. **13**J, the base layer **202** may be different from the substrate **192** associated with block **1410**. The base layer **202** may be deposited over the inner conductive layer **107** and serves as the actual bottom substrate of the metamaterial device once the vias are turned over. The base layer **202** may fill the vias **1103** creating bristles with solid cores. Alternatively, as shown in FIG. **13**J, the base layer **202** may not fill the vias **1103**, creating bristles with non-solid cores. Regardless, the base layer **202** may be deposited over the inner conductive layer **107** by any method known in the art.

[0142] In block **1426** the metamaterial may be turned over as shown in FIG. **13**K, so that the bristles are turned upright presenting the original substrate **192** covering the outer conductive layer **103** at the top and the base layer **202** at the bottom of the device. In optional block **1460** the substrate may be further processed, such as to form an anti-reflection layer or rough outer surface **192***a* as shown in FIG. **13**L.

[0143] In an alternative embodiment method, lasers **2401** may create vias **1103** out of a substrate or index matched material as illustrated in FIGS. **13**M through **13**O. The lasers **2401** may be controlled in terms of exposure time and energy in order to control the depth and size of the vias. After creating the vias **1103**, the method **1400** operations described above with references to blocks **1421**, **1448**, **1452**, **1440**, **1442**, **1446**, **1442**, **1422**, **1424**, **1426**, **1458**, and **1460** may be followed.

[0144] Stamps may create vias out of a substrate such as a transparent polymer. When using a polymer, a UV source may cure the stamped vias creating a more rigid structure followed by adding conductive layers, absorber layers, and a base layer. The stamping via method for forming an array of bristles for a metamaterial device is illustrated in FIGS. **15**A-**15**J and FIG. **16**.

[0145] In block **1608** an array of vias may be formed out of the processed polymer. As illustrated in FIGS. **15**A-**15**B, a stamping process may be used to create vias **1103** out of a polymer substrate **192**. In block **1610** the formed polymer may be cured or otherwise treated to yield desired material properties. For example, such curing/treating may include heating and/or exposure to an ultraviolet light source **193**.

[0146] The stamping process may include a rolling press or rolling die to create vias **1103** on a substrate **192** similar to FIG. **15**B. When using a rolling press or a rolling die, a roll-to-web and a web-to-plate sub-process may create the associated stamps and vias method **1600**. The rolling press or rolling die sub-process is described in more detail below with reference to FIGS. **33**A-**33**G, **34**, **35**A-**35**E, **36**A-**36**E.

[0147] Similar to method **1400**, the method **1600** includes laying down the outside layers of the photovoltaic bristles are laid down first, so conductive traces used to draw current from the photovoltaic cells may be laid down prior to the outer conductive layer **103**. Thus, in optional block **1612**, conductive traces may be applied to the substrate. Vias for such conductive traces may be formed as part of the operations in blocks **1608**-**1610**. Alternatively, conductive traces may be applied to the substrate using dedicated photolithography steps, laser ablation steps, and deposition steps such as those described above and below. In particular embodiment, the method may include applying conductive traces using a spray jet techniques. In block **1622** an outer conductive layer may be deposited in the vias. If conductive traces are added prior to the outer conductive layer **103**, the method may include depositing the outer conductive layer **103** over the conductive traces as a conformal film. As illustrated in FIG. **15**D, the outer conductive layer **103** may be deposited over the polymer **192** and in the vias **1103**.

[0148] Although it is not shown in FIGS. **15**A-**15**J, multiple outer conductive layers **103** or sublayers may be applied. So, in optional block **1652** additional outer conductive layers may be applied over the previous layer.

[0149] As shown in FIGS. **15**E-**15**F, in block **1640** a first absorber layer may be applied over the outer conductive layer(s), and in block **1642** a second absorber layer may be deposited over the first absorber layer. The method may deposit the first and second absorber layer **104**, **105** by chemical vapor deposition. In optional block **1646** additional absorber layers may be deposited over the other absorber layers in a manner similar to the process steps in blocks **1640** and **1642**.

[0150] As shown in FIG. **15**G, in block **1648**, an inner conductive layer **107** may be applied over the last absorber layer (e.g., second absorber layer **105**), such as by chemical vapor deposition or physical deposition. The inner conductive layer **107** may also include multiple layers similar to the outer conductive layer **103** earlier described with reference to blocks **1622**, **1650**, and **1652**.

[0151] As shown in FIG. **15**H, in optional block **1624** a base layer may be applied. The base layer **202** may be different from the polymer **192** applied in block **1608** because the base layer **202** is deposited over the inner conductive layer **107** and serves as the actual bottom substrate of the metamaterial device once turned over. Although the polymer **192** may be of the same material as the base layer **202**, the polymer **192** may serve as an outer transparent coating to the metamaterial device once the metamaterial is complete. The base layer **202** may fill the vias **1103** creating bristles with solid cores. Alternatively, as shown in FIG. **15**J, the base layer **202** may not fill the vias **1103**, creating bristles with non-solid cores. Regardless, the base layer **202** may be deposited over the inner conductive layer **107** by any method known in the art.

[0152] As shown in FIG. **15**I, in block **1626** the metamaterial may be turned over for further processing. In optional block **1660** the substrate **192** may be processed to give it desired physical properties, such as hardening or polishing. The processing may include forming an antireflection layer or rough outer surface **192***a* as shown in FIG. **15**J.

[0153] In a further embodiment method that uses some of the same processes as in method **1600**, material **1112** in which vias **1103** are poured into a mold **1110** instead of being pressed, as illustrated in FIGS. **15**K through **15**M. As illustrated in FIG. **15**K, instead of a die, the same basic shape may be inverted to form a mold **1110** onto which may be poured the material **1112** to form the vias **1103** and supporting substrate. This material **1113** may be a transparent plastic, polymer or glass that will ultimately have the desired optical properties in the finished product. In this embodiment, the operations of forming the array of vias **1103** in block **1608** include pouring the base material **1112** into the mold **1110**, sufficiently covering the mold surface to provide a substrate **1112** as shown in FIG. **15**L. The material may be cured in block **1610** in this state before the mold **1110** is removed as shown in FIG. **15**M. Thereafter, the operations of depositing outer conductive layers, absorber layers and inner conductors may be accomplished as described above with reference to blocks **1612**-**1626**.

[0154] As a further alternative embodiment, vias may be formed by adding an index-matched nano-imprinted layer over a substrate. The nano-imprinted layer comprises the vias for methods **1200**, **1400**, **1600** and may use suitable nano-imprinting techniques known in the art. For example, methods **1200**, **1400**, and **1600** may include depositing a nano-imprinted layer material with an index of refraction of 1.5 over a glass or polymer substrate.

[0155] As mentioned with reference to block **808** of FIG. **8** forming an array of cores out of the processed polymer may include using a rolling die or rolling press. Similarly, with reference to block **1608** of FIG. **16**, forming an array of vias may also include using a rolling die or rolling press. Although a rolling press may be directly applied to a substrate or a moldable layer on top of the substrate, using such a method may damage a master template having a particular pattern for creating the cores or vias. Thus, to increase yield and throughput of creating substrates with an array of cores or vias, a master template may be used to create daughter templates on a web, and each daughter template web may be applied to a substrate to create the desired core or via pattern in a surface material that will be subsequently processed to form the solar arrays. For example, a master template including cores may imprint vias on a substrate applied to a web creating a daughter template. The daughter template with vias may then be applied to a substrate to create cores on the substrate. After curing to increase material strength of the newly formed cores, the substrate may be further processed using embodiment methods such as described above with reference to FIG. **8** and blocks **810**-**858**. As an alternative example, a master template including vias may be applied to a substrate on a web to create a daughter template featuring rods that may then be applied to a substrate to imprint vias into the substrate (or a layer over a substrate). The via imprinted substrate may be further processed using embodiment methods such as described above with reference to FIG. **16** and blocks **1612**-**1660**.

[0156] An embodiment method **3400** for manufacturing an array of cores for photovoltaic bristles using a rolling press or die is illustrated in FIGS. **33**A-**33**G and FIG. **34**. Using a rolling press or die method as described below may enable processing methods that reduce the number of defects in fabricating photovoltaic bristles by creating reusable master templates and daughter dies that can be inspected with inspection results used in a feedback control system to bypass imperfect portions.

[0157] Referring to FIGS. **33**A-**33**G and FIG. **34** together, in block **3402** of method **3400** an original master may be created to form a patterned array of bristles for the metamaterial device. Stamping processes such as nano-imprint lithography may create the original master **3306** with rods **3308** from a flexible material as illustrated in FIGS. **33**A and **33**B. Any known process in the relevant art may be used to create such master templates. Companies such as EVG, Obducat, NIL Technology, Nanoex, Molecular Imprints, and Sú Microtech work with nanoimprint lithography and have refined reliable nanoprint lithography techniques. As an alternative, traditional photolithography also may create the original master.

[0158] If using nanoimprint lithography, the process may include imprinting the desired pattern onto the original master **3306** created out of a flexible material such as a polymer or polydimethylsiloxane (PDMS). In optional block **3404** a suitable metal, such as nickel, may be electroformed over the original master to create a rigid master template or shim. Such metal plating may also be applied after the master is formed into or onto a roller as described below with reference to block **3408**. The rigid master template may be used to create flexible master templates such as the master webs described below. Whether created by the rigid master template or formed as the original master, flexible templates such as PDMS may be used to imprint patterns on more rigid materials.

[0159] The master template may be formed in one piece, or a large master template may be formed from stitching together the master template in block **3406**. Whether the master template is flexible or rigid, multiple masters may be stitched together as illustrated in FIG. **33**C. Once the large master template is formed, in block **3408**, the large master template may be wrapped around a drum roller (or formed into a roller) as illustrated in FIG. **33**D. The drum roller may then be used for subsequent processing in a roll-to-web system as described below.

[0160] The web material may be a polymer or polyester film, such a Dupont's Mylar®. By way of example, the web material may have a thickness of 25 to 250 microns, a length of 100 to 2000 feet, and a width of 0.5 to 6 feet. In block **3410** a first moldable material, such as a lacquer, spin-on-glass coatings, a sol-gel, or PDMS, may be applied to a web to coat a thin layer of the material over the web. Since the web itself is flexible, a flexible material such as PDMS may be less restricting than sol-gel, spin-on-glass coatings when moving through the rollers and subsequent processing.

[0161] In block **3412** the first pattern from the large master template may be imprinted to the coated web to create a second imprint pattern on the web as illustrated in FIG. **33**E. In this process operation, the drum roller with a rod pattern imprints vias **3314***b* into the coated material on the web by pressing the web and the coated material against a transfer spacing roller **3318**. Alternatively, the drum roller with a via pattern creates a rod pattern from the coated material on the web (not shown). In block **3414** the second imprint pattern on the web may be cured or otherwise processed to increase its material strength. An ultra violet light or a thermal mechanism for applying heat may be used to cure the second imprinted pattern. If using PDMS as a moldable material, a thermal mechanism may apply heat to cure the imprinted pattern. The result of these processor operations is a daughter die web suitable for use in subsequent operations for creating a substrate with cores (or alternatively vias) on a substrate that will eventually become solar cells. As an alternative embodiment method, the web itself may be a flexible substrate and with a cured second imprinted pattern the web substrate may be suitable for use in embodiment methods (e.g., method **800** or **1600**) describe herein to create metamaterial devices.

[0162] In block **3416** the master web may be installed on rollers in a web-to-plate process. In block **3418** a moldable material may be applied to a substrate or surface on which the solar arrays will be formed. For example, the moldable material may be a polymer that can be cured (e.g., by exposing it to ultra violet radiation) after it is applied to a substrate or support surface and imprinted as described below. As another example, the moldable material may be a flexible thermally curable sol-gel that is applied to a substrate or support surface and imprinted as described below. Alternatively, the substrate itself may be a moldable material and thus the operations in block **3418** may involve creating the substrate of moldable material.

[0163] As illustrated in FIG. **33**F, the second pattern from the master web may be imprinted on the moldable material to create a third imprint pattern on or in the substrate in block **3420**. In the example illustrated in FIG. **33**F, a daughter die web with vias **3314***b* will form cores **3320***a* of the moldable material **3320** on the substrate **3322**. As described below, the process pressing the daughter die **3316** into the moldable material **3320** on the substrate **3322** may be controlled so that the two surfaces come together without sliding, which could deform or fail to form the desired cores **3320***a* (or vias).

[0164] In block **3422** the cores **3320***a* (which are the third imprinted pattern) illustrated in FIG. **33**G or vias (not shown) may be cured or otherwise processed to increase their strength and rigidity before subsequent processing according to embodiment methods described above with reference to FIGS. **8** and **16**. As mentioned above, such curing or processing of the cores or vias may involve exposure to ultra violet light (e.g., to increase cross linking in a polymer material) or heating (e.g., to convert sol gel into a glass or ceramic).

[0165] FIG. **35**A illustrates an embodiment roll-to-web system **3500** suitable for use in the operations described above with reference to blocks **3406**-**3414** in method **3400**. The illustration of the roll-to-web system **3500** in FIG. **35**A and the following description is provided as an illustrative example and is not intended to limit the scope of the claims as other roll-to-web system configurations (e.g., different roller configurations, different web paths and different sequences of operations) are possible without departing from the scope of the present invention.

[0166] In the embodiment roll-to-web system **3500** illustrated in FIG. **35**A, a web material may pass through a series of rollers configured and controlled to maintain tension and orientation, apply a moldable material to the web, and imprint a first pattern from a master die on the moldable material to create a second pattern of cores or vias in the moldable material. That second pattern of cores or vias in the moldable material may be subsequently cured/processed to form the daughter die on the web.

[0167] The roll-to-web system **3500** may include an unwind roller **3502** that may be driven by an unwind motor **3502***a* connected to an unwind motor controller **3502***b* to control the rotation of the unwind roller. An uncoated web **3501***a* may be installed on the unwind roller **3502** and be unwound throughout the roll-to-web system **3500**. From the unwound roller **3502**, the uncoated web **3501***a* may roll over a tension sensor **3312**. The tension sensor may provide web-tension information to the unwind motor controller **3502***b* which may use this information as feedback along with torque sensing feedback from the unwind motor **3502***a* to control web tension through the roll-to-web system **3500**.

[0168] The uncoated web **3501***a* may travel over a tracking roller **3504**, which may be adjusted by the control system to control the lateral position of the web in the system in response to signals from an edge sensor **3505**. By adjusting the tracking roller **3504**, the web's position on the rollers may also be adjusted to an optimum position/orientation to prevent skewing of the pattern on the web. For example, if the web is too far to the left side of the rollers, the tracking roller may be adjusted to move the web back toward the center of the rollers.

[0169] The uncoated web **3501***a* may travel through S-wrap rollers **3506**, which control the velocity and tension of the web **3501** as it passes through the roll-to-web system **3500**. The S-wrap rollers **3506** may adjust the velocity of the web **3501** traveling through the roll-to-web system **3500** based on data from drum roller speed encoders **3521**. In this manner, the S-wrap rollers may serve to synchronize the speed of the web as it meets with the drum roller (which includes the master die) that imprints the pattern on the web **3501**. Closely controlling the relative speed of the web and the drum roller reduces the chance for defects to be printed on the daughter dies as well as the chance for damaging the master die on the drum roller.

[0170] The uncoated web **3501***a* may travel between a transfer roller **3507** and a rubber roller **3508**. The transfer roller **3507** picks up a layer of moldable material **3509** and applies the layer to the web, while a shear roller **3510** ensures the applied layer is of the desired thickness. As the uncoated web **3501***a* travels between the rubber roller **3508** and the transfer roller **3507**, the transfer roller **3507** collects the moldable material **3509** on the transfer roller **3507**. Prior to the transfer roller **3507** applying the first moldable material **3509** to the uncoated web **3501***a*, the shear roller **3510** removes excess moldable material **3509** from the transfer roller **3507** to ensure a consistent coating on the web **3501***a*. A rubber roller **3508**, potentially made of high durometer ground rubber, may provide support to the web **3501** while the transfer roller **3507** applies the first moldable material **3509**.

[0171] After the transfer roller **3507** applies the first moldable material **3509** to the uncoated web **3501***a*, a thickness sensor **3511** may measure the thickness of the first moldable material **3509** on the coated web **3501***b*. The thickness sensor may be used by a control system that may send a signal to cause the shear roller **3510** shift position in order to maintain a consistent thickness and compensate for any thickness variations in the uncoated web **3501***a*. For example, if the thickness sensor indicates the coated web's thickness is higher than a set point, control system may cause the shear roller **3510** to move closer to the transfer roller **3507**, thereby removing more of moldable material **3509** from the transfer roller **3507** prior to its application to the uncoated web **3501***a*.

[0172] The coated web **3501***b* passes between the drum roller **3512**, which includes the master template, and a transfer spacing roller **3513** in order to imprint the daughter die pattern in the moldable material on coated web **3501***b*. The moldable material on the coated web **3501***b* accepts the first pattern as the coated web **3501***b* is pressed against the drum roller **3512** to create a second pattern in the moldable material **3509**. The speed of rotation of the drum roller **3512** is closely controlled by a control system so that it spins in conformity with the speed of the moving web **3501** to precisely imprint the first pattern on the web. To do so, the control system may receive signals from speed encoders **3521** coupled to the S-wrap roller(s) **3506** and use this information in a closed-loop control algorithm to ensure that the surface of the drum roller matches the speed of the web **3501** passing beneath or over it. Depending on the type of moldable material, the imprinted web **3501***c* may be cured/processed (e.g., thermally or with ultra violet light) by a curing mechanism **3514**.

[0173] The cured web **3501***d* may travel over a support roller **3515** and a second tension sensor **3516** prior to being collected on a wind roller **3518**. The wind roller **3518** may be driven by a wind motor **3518***a* controlled by a wind motor controller **3518***b*. The wind motor controller **3518***b* may adjust the wind up speed of the wind roller **3518** based on the torque of the wind motor **3518***a* and signals from the second tension sensor **3516** to assist in maintaining proper web tension and a speed of advance.

[0174] The roll-to-web system **3500** may also include an inspection camera **3519** that may scan the cured web **3501***d* for defects. Images from the inspection camera **3519** may be processed by a computer to identify areas of defects, which may be recorded against position on the web in a web-mapping database **3520** that may be used in controlling the final printing process. As described below, a web-to-plate system **3600** may access the web-mapping database **3520** and adjust its system parameters (e.g., web speed, substrate linear speed, sheet gap mechanism) to avoid applying any mapped defects in the web **3501***d* to substrate being processed in such a system.

[0175] The roll-to-web system may also include a moldable material processing system **3522**. The moldable material processing system **3522** may be fluidly connected to a moldable material container that houses the moldable material **3509** for the transfer roller **3507**. The moldable material processing system **3522** may recirculate the moldable material **3507** through system components (filters, heat exchangers, etc) to ensure the moldable material **3507** is clean and at the proper temperature for applying to the web **3501***a*. The moldable material processing system **3522** may add moldable material **3509** as needed to ensure ample moldable material for the roll-to-web system **3500**.

[0176] Various portions of the roll-to-web system **3500** may be subject to humidity and temperature controlled to ensure that the moldable material **3509** adheres to the web **3501** and that the moldable material **3509** accepts the desired pattern from the drum roller **3512** with minimal defects. This may be especially important if the moldable material **3509** is a sol-gel or other thermally cured material.

[0177] FIGS. **35**B-**35**E illustrate example control systems that may be used to control various portions and components of the roll-to-web system **3500** described above enable high precision printing from the drum roller **3512** to the web **3501**. FIG. **35**B illustrates the electrical controls between the tension sensor **3503**, the unwind motor **3502***a*, and the unwind motor controller **3502***b*. The unwind motor controller **3502***b* may utilize a PID controller system which adjust the unwind motor **3502***a* based on inputs from the tension sensor **3503**, a tension sensor set point, a torque input from the unwind motor **3502***a*, and a torque set point. A skew actuator controller **3504***a* illustrated in FIG. **35**C may adjust the position of the tracking roller **3504** based on data from the edge sensor **3505** and a set point. An S-wrap motor controller **3506***a* illustrated in FIG. **35**D may control speed of the s-wrap rollers **3506** and the corresponding web velocity through the roll-to-web system. The S-wrap motor controller **3506***a* controls S-wrap rollers **3506** to synchronize the web velocity with the drum roller's rotational speed based on data from the speed encoder **3521** and a set point. The wind motor controller **3518***b* illustrated in FIG. **35**E is similar to the unwind motor controller **3502***b* illustrated in FIG. **35**B, except that the wind motor controller **3518***b* accepts input data based on the second tension sensor **3516**, a tension set point, torque data from the wind control motor **3518***a*, and a torque set point.

[0178] FIG. **36**A illustrates an embodiment web-to-plate system **3600** that may be suitable for forming the desired pattern of cores or vias on the substrate as described above with reference to blocks **3416**-**3422** in method **3400**. The illustration of the web-to-plate system **3600** in FIG. **36**A and the following description is provided as an illustrative example and is not intended to limit the scope of the claims as other web-to-plate system configurations (e.g., different roller configurations, different web paths and different sequences of operations) are possible without departing from the scope of the present invention.

[0179] The web-to-plate system **3600** may process a substrate that moves through the system on a linear drive mechanism by applying a moldable material to the surface of the substrate. As an alternative, if the substrate is the second moldable material then a moldable material does not need be added to the substrate. The moldable material applied to the substrate in this process may be different from the moldable material that is applied to the web and used to form the daughter die pattern. The web-to-plate system **3600** also passes the daughter die web (which has the second template pattern as described above) through a series of rollers that control its tension and speed of advance, and presses it onto the moldable material the substrate to create a third pattern, which is the desired cores or vias. The web-to-plate system **3600** has a web subsection and a plate subsection. The web subsection will be discussed first. The web-to-plate system **3600** may also include a module or apparatus that cures/processes the third pattern in order to produce the substrate with a pattern of cores or vias suitable for the embodiment processes described above with reference to FIGS. **8** and **16** for applying photovoltaic materials.

[0180] The web **3501***d* on the web-to-plate system **3600** is weaved through various rollers to control tension and position, similar to the roll-to-web system **3500**. The web-to-plate system **3600** may include an unwind roller **3602** driven/controlled by an unwind motor **3602***a* connected to an unwind motor controller **3602***b* configured to control the rotation of the unwind roller **3602**. The daughter die web **3501***d* from the roll-to-web process described above may be installed on the unwind roller **3602**. The daughter die web **3501***d* may travel across a tracking roller **3603** and an edge guide sensor **3604**. The edge guide sensor **3604** may collect information regarding the position of the web **3501***d* on the rollers relative to a set point and send that data to a controller of the tracking roller **3603** so the position/orientation of the tracking roller **3603** can be adjusted to correct the orientation of the daughter die web **3501***d* in the system and prevent web skewing within the rollers. The web-to-plate system **3600** may include a tension sensor **3606** that provides data to an unwind motor controller **3602***b* to enable the unwind motor controller **3602***b* to control the unwind motor **3602***a* to adjust the speed of the unwind roller **3606** based on tension data. The unwind motor controller **3602***b* may also use torque data from the unwind motor **3602***a*. Unlike the roll-to-web system **3500**, in the web-to plate system **3600** the same tension sensor **3606** may also be connected to the wind motor controller **3608** to enable the wind motor controller **3608***b* to control the wind motor **3608***a* to adjust the speed of the wind roller **3608** based on the same tension data. The tension sensor **3606** may be positioned after the velocity roller **3605**.

[0181] The web-to-plate system **3600** may not include S-wrap rollers to control the velocity of the web. Instead, the web-to-plate system **3600** may use a velocity roller **3605** to perform a similar function. The velocity roller **3605** may be connected to a velocity roller motor controller **3605***a*, which may adjust the velocity of the daughter die web **3501***d* to match the linear speed of the substrate based on data acquired from the linear drive controller **3601***a*. The velocity roller controller **3605***a* may also adjust the speed of the web **3601***d* based on web-mapping data from the web-mapping database **3520**. For example, if there is a defect in the daughter die web, the velocity roller **3605** may increase the velocity of the daughter die web **3601***d* at a certain point in time to ensure that the defected portions are not imprinted on the substrate **3609***a*. Alternatively or in addition, the linear drive controller **3601***a* may be controlled to pause the advance of the substrates in order to enable a portion of the daughter die web with a defect to be advanced before imprinting of the next substrate begins.

[0182] The daughter die web **3501***b* may travel around the velocity roller **3605** past the tension sensor **3606** to a transfer gap roller **3607**. The transfer gap roller may aid in pressing the daughter die web **3501***d* against the substrate to imprint the second pattern into moldable material on the substrate **3609***a* thereby creating the third pattern of cores or vias. Once the daughter die web **3501***d* imprints the second pattern on the substrate **3609***a*, the daughter die web **3501***d* may be wound around the wind roller **3608** and used for future processing.

[0183] The plate subsection of the web-to-plate system **3600** includes a linear drive mechanism **3610** configured to control the linear motion and linear velocity of the substrate **3609** through the web-to-plate system **3600**. The linear drive mechanism **3610** is connected to a linear drive controller **3610***a*, which may control the speed of the substrate **3609** in the web-to-plate system **3600** based on data from the sheet gap controller **3611***a*, the web-mapping database **3520**, and the velocity roller motor controller **3605***a*.

[0184] While the preprocessed substrate **3609***a* is traveling across the linear drive mechanism **3610**, the sheet gap mechanism **3611** may stop the preprocessed substrate **3609***a* by a vertical actuation synchronized with the movement of the substrate **3609** and the daughter die web **3501***d* to reduce imprinting defects. For example, the sheet gap controller **3611***a* may receive web-mapping data regarding a known defect on the daughter die web's pattern from the web-mapping database **3520**, and in response control the sheet gap mechanism **3611** to stop the substrate **3609***a* from moving forward in the system when a defective portion of the daughter die web is present on or near the transfer gap roller **3607** to avoid printing a defect from the daughter die web **3501***d* on to the substrate **3609***a*. As another example, the sheet gap mechanism **3611** may prevent the substrate **3609***a* from moving to the second moldable material applicator **3612**, while the moldable material application is adjusted, refilled, etc. When the sheet gap mechanism is actuated a sheet gap sensor or trigger may act as an input to other controllers in the system.

[0185] After passing the sheet gap mechanism **3611**, a moldable material applicator **3612** may apply the moldable material **3613** over the substrate to create a coated substrate **3609***b*. A thickness sensor **3614** may detect the thickness of the moldable material on the coated substrate **3609***b* and provide feedback to the moldable material applicator **3612** for adjusting the amount of moldable material applied to the substrate **3609***a*. The coated substrate **3609***b* contacts the daughter die web **3501***d* with pressure applied by the transfer gap roller **3607** so that the second pattern from the daughter die web **3501***d* is imprinted on the coated substrate **3609***b* to create an imprinted substrate **3609***c*.

[0186] Depending on the type of moldable material, the imprinted substrate **3609***c* may be cured or processed to increase its material strength, such as via thermal and/or ultra violet radiation curing in a curing mechanism **3615**. After curing, the final substrate **3609***d* is ready for further photovoltaic processing according to an embodiment method described above with reference to FIG. **8** or FIG. **16**. Further processing may include adding absorber layers, inner conductive layers, outer conductive, microtraces, etc.+

[0187] FIGS. **36**B-**36**E illustrate control systems that may be configured to enable high precision printing from the web to the substrate in the web-to-plate system **3600**. FIG. **36**B illustrates electrical controls between the tension sensor **3606**, the unwind roller motor **3602***a*, and the unwind motor controller **3602***b*. The unwind motor controller **3502***b* may utilize a PID controller system that adjusts the unwind motor **3602***a* based on inputs from the tension sensor **3606**, a tension sensor set point, a torque input from the unwind motor **3602***a*, and a torque set point. The tension input may be used as the lowest level input variable and torque from the unwind motor **3602***a* and the wind motor **3608***a* may be the major control variables. The unwind and wind motor controllers **3602***b* and **3608***b*, respectively, will look for a minimum value from the tension sensor **3606** to insure the web has tension. The differential between the wind/unwind torque and a respective set point may be used to determine dynamic wind or unwind force to be applied in order to maintain a desired tension. The wind and unwind controller **3602***b* and **3608***b* will evaluate the differential between the two motor systems to control the web tension. Software may run linear and non-linear proportional loop equations based on an input factor. The integral portion will smooth the interactions and the integral sample rate within a sample window. Due to the sensitive nature of the process and the time constants involved, the derivative portion may act as a dampener. Similar logic may be applied to the control of the roll-to-web system **3500**. Further details regarding PID logic and control loops may be found in U.S. Pat. No. 4,500,408, entitled Apparatus for and Method of Controlling Sputter Coating.

[0188] A skew actuator controller **3603***a* illustrated in FIG. **36**C may adjust the position of the tracking roller **3603** based on data from the edge sensor **3604** and a set point. A velocity controller **3605***a* may control the speed of the velocity roller **3605** and the corresponding web velocity through the web-to-plate system **3600** as illustrated in FIG. **36**D. The velocity motor controller **3605***a* may control the velocity roller **3605** to synchronize the web velocity with the linear drive speed controlled by the linear drive controller **3610***a*. The wind motor controller **3608***b* illustrated in FIG. **36**E is similar to the unwind motor controller **3602***b* of FIG. **36**B, except that the wind motor controller **3518***a* may accept input data based on torque data from the wind control motor **3518***a*, and a torque set point.

[0189] FIGS. **17-21** illustrate multiple embodiment metamaterials **1700**, **1900**, **2100** with current conducting traces **1701**, **1702**, **1703**, **1901**, **2101** applied to reduce electrical resistance within the metamaterials. The current conducting traces **1701**, **1702**, **1703**, **1901**, **2101** provide an electrical path for flowing electrons from the outer conductive layer **103** in metamaterials **200**, **300**, **400** to collector contacts on the edges of the cells. Electrons may travel from the outer conductive layer **103** via the current conducting traces **1701**, **1702**, **1703**, **1901**, **2101** to the outer edge of the metamaterials **1700**, **1900**, **2100** where they connect to bus bars or high capacity conductors. By reducing the electrical resistance within metamaterials **1700**, **1900**, **2100** less electrical energy will be converted to heat and more electrical power may be produced. The embodiment metamaterials **1700**, **1900**, **2100** described below may include current conducting traces **1701**, **1702**, **1703**, **1901**, **2101** in any combination or sub-combination.

[0190] FIG. **17** illustrates a cross-sectional side view of a metamaterial **1700**, which is similar to metamaterial **200** but with current conducting traces **1701**, **1702**, and **1703**. In an embodiment, metamaterial **1700** may include current conducting trace **1701** on top of the outer conductive layer **103** of a row of shorter photovoltaic bristles **1704**. Although FIG. **17** shows only one row of shorter photovoltaic bristles **1704** with a current conducting trace **1701** on the shorter photovoltaic bristles **1704**, in an embodiment there may be multiple rows of shorter photovoltaic bristles **1704** with current conducting traces **1701** on top.

[0191] In an embodiment, metamaterial **1700** may include current conducting traces **1702**, **1703** in different locations than current conducting trace **1701**. As with the current conducting trace **1701**, metamaterial **1700** may include current conducting trace **1702** on top of the outer conductive layer **103** but positioned at the end of the array of photovoltaic bristles **201**. Metamaterial **1700** may include current conducting trace **1703** on top of the substrate **202** or in contact with the inner conductive layer **107** to allow efficient electron flow. Electrons may flow from the absorber sublayer **105** to the outer conductive layer **103** through the current conducting traces **1701**, **1702** to the electrical destination (e.g., electrical storage, electrical converter, or motor) and the circuit is completed by connecting current conducting trace **1303** to the inner conductive layer **107** or metal substrate **202**. Alternatively, electrons may flow from the absorber layer **105** through the inner conductive layer **107** to the current conducting trace **1303** and then to an electrical destination (e.g., electrical storage, power converter, etc).

[0192] FIG. **18** illustrates the top view of FIG. **17** of metamaterial **1700** with current conducting traces **1701**, **1702**, **1703**. In an embodiment, metamaterial **1700** may include current conducting trace **1701** on top of an array of shortened photovoltaic bristles **1704** extending along the width of the array. Similarly, current conducting traces **1702** and **1703** may extend along in the same direction of the array. Connecting current conducting traces **1701** and **1702** to current conducting traces **1703** may create a complete circuit in the metamaterial **1700**, thereby allowing current to flow through the array of bristles when struck by photons sufficient to generate electron movement.

[0193] FIG. **19** illustrates a cross-sectional side view of a metamaterial **1900**, which is similar to metamaterial **200**, but with current conducting traces **1901**, **1702**, **1703**. In an embodiment, metamaterial **1900** may include current conducting trace **1901** on the outer conductive layer **103** between the photovoltaic bristles **201**. As with FIG. **17**, metamaterial **1900** may include current conducting traces **1702** on the outer conductive layer **103** and current conducting traces **1703** on the substrate **202** and/or in contact with the inner conductive layer **107**. In contrast with FIG. **17**, metamaterial **1900** may not include a row of shorter photovoltaic bristles **1704** because current conducting traces **1901** are between the photovoltaic bristles **201** on top of the outer conductive layer **103**. However, in an embodiment, metamaterial **1900** may include a row of shorter photovoltaic bristles **1704** with a current conducting trace **1701** on the shorter photovoltaic bristles

1704 in addition to the current conducting traces **1901** positioned between photovoltaic bristles **201**.

[0194] FIG. **20** illustrates the top view of FIG. **19** of an array of photovoltaic bristles **201** on a flat substrate **202** with current conducting traces **1901** positioned between photovoltaic bristles **201**. Similar to the current conducting traces **1701**, **1702**, **1703** in FIG. **18**, the current conducting traces **1901**, **1702**, and **1703** extend the entire width of the array. In an embodiment, the current conducting traces **1901**, **1702**, **1703** may extend in any direction. For example, the current conducting traces **1901**, **1702**, and **1703** may extend diagonally, along the length, and/or along the width of the metamaterial **1900**.

[0195] FIG. **21** illustrates a cross-sectional side view of a portion of metamaterial **2100** similar to metamaterial **300**, but with current conducting traces **2101**, **1702**, **1703**. Metamaterial **2100** includes current conducting trace **2101**, which may be located between photovoltaic bristles **301** as well as at the peak and trough of the slanted substrate surfaces **308***a*, **309***a*, **308***b*, **309***b*. In an embodiment, metamaterial **2100** includes current conducting traces **1702**, **1703** at the ends of the metamaterial **2100** similar to FIGS. **17** and **19**. Current conducting trace **1702** may be on the outer conductive layer **103** at the ends of the array of photovoltaic bristles **301**. Current conducting trace **1703** may be on top of the substrate **302** and/or in contact with the inner conductive layer **107**. In an embodiment, metamaterial **2100** may include current conducting traces **2101** on top of the outer conductive layer **103** and between photovoltaic bristles **301** located on the peak and/or the trough of the slanted substrate surfaces **308***a*, **309***a*, **308***b*, **309***b*. Although it is not shown in FIG. **21**, the metamaterial **2100** may have current conducting traces **2101** positioned on the outer conductive layer **103** on top of shorter photovoltaic bristles **1704** as shown in FIG. **17**. In an embodiment, metamaterial **2100** may be similar to metamaterial **400** as it may be without photovoltaic bristles **401** on slanted substrate surfaces **409***a*, **409***b*. For example, the metamaterial may include current conducting traces **2101** between photovoltaic bristles **401** only on alternating slanted substrate surfaces **408***a*, **408***b*, etc.

[0196] Photolithographic techniques may be used to deposit the current conducting traces **1701**, **1702**, **1703**, **1901**, and **2101** of FIGS. **17-21** on metamaterials **200**, **300**, and **400**. These current conducting traces may be added to the metamaterials regardless of whether the metamaterials are created through stamping, vias, or any other technique. Although photolithographic techniques are used for adding each current conducting trace **1701**, **1702**, **1703**, **1901**, and **2101** to the metamaterial device, when adding current conducting trace **1703** to a metamaterial a different method may be used. Thus, FIGS. **22A-22H** illustrate and FIG. **23** describes the method steps for forming current conducting traces **1701**, **1702**, **1901**, and **2101**, while FIGS. **24A-24J** illustrate and FIG. **25** describes the methods steps for forming current conducting trace **1703**. Each method is discussed in turn.

[0197] Current conducting traces **1701**, **1702**, **1901**, and **2101** may be formed on metamaterials **200**, **300**, and/or **400**. In block **2302** a photoresist layer may be deposited over the metamaterial. As shown in FIGS. **22A** and **22B**, a photoresist layer **189** may be deposited over the metamaterial. In block **2304** a mask may be positioned over the photoresist layer. In block **2306** the photoresist layer may be exposed to UV light through the mask. As illustrated in FIG. **22C**, exposing only a portion of the photoresist **189** to UV radiation creates an exposed portion **189***a* within the photoresist layer **189**. In block **2308** the photoresist layer **189** may be "developed" by exposing it to chemicals that remove the exposed portions **189***a* leaving a protective template, and the assembly may be etched to create pores **189***b* shown in FIG. **22D**. In optional block **2310** the substrate may be etched through the template. This step may be required when the metamaterial is formed with vias in methods **1400** or **1500**. When creating photovoltaic bristles using vias, the original substrate **192** (shown in FIGS. **13K** and **15I**) may form a protective coating over the bristles. Thus, the method may include an etching step to expose the outer conductive layer **103** through the substrate **192** before depositing current conducting traces **1701**, **1702**, **1901**, and **2101** on the outer conductive layer **103** eventually followed by filling the etched void in the substrate **192** with a transparent coating. In block **2322** a current conducting trace may be deposited on the metamaterial. Current conducting traces **1701**, **1702**, **1901**, and **2101** may be deposited on the outer conductive layer **103** through photoresist template as shown in FIG. **22E**. In block **2312** the photoresist layer may be removed. As shown in FIG. **22F**, when the photoresist **189** is removed, only the bristles and the current conducting trace remains. After removing the photoresist, a transparent coasting may be applied to the solar cell covering the bristles and the deposited current conducting trace.

[0198] As an alternative to photolithographic techniques, a method for depositing the current conductive traces may include an ink jet device **2201** illustrated in FIGS. **22G** and **22H** to reduce manufacturing cost. The ink jet **2201** may deposit a conductive trace **1901** in desired locations (e.g., between bristles) by using colloidal material such as silver without the use of the multiple steps associated with photolithographic techniques. Thus, this alternative may include only one-step of depositing a conductive trace on the metamaterial in block **2322**.

[0199] Current conducting trace **1703** may be formed by a different method as illustrated in FIGS. **24A-24J** and FIG. **25**. In block **2502** a first photoresist layer may be deposited over the metamaterial. As shown in FIG. **24A**, a first photoresist layer **189** may be deposited over and between the bristles of the metamaterial. In block **2504** a first mask may be positioned over the first photoresist layer. As shown in FIG. **24B**, the first mask **195** may block UV radiation to the photoresist **189** except through mask portion **195***a*. This controls the UV radiation to the desired portion of the photoresist layer **189**. In block **2506** the method may include exposing a UV source to the first photoresist layer through the first mask to create an etching template. As illustrated in FIG. **24B**, exposing only a portion of the photoresist layer **189** to UV radiation creates an exposed portion **189***a* within the photoresist layer **189**. After creating the exposed portion **189***a* within the photoresist, the mask may be subsequently removed from the metamaterial. In block **2508** the first photoresist layer may be developed. For a positive photoresist layer this includes removing the exposed portion **189***a* leaving a template created by the remaining photoresist layer **189** with pores **189***b* as shown in FIG. **24C**. In block **2510** the method may include etching the metamaterial through the etching template. As illustrated in FIG. **24D**, the photoresist template **189** controls the etching process by removing only a portion of the outer conductive layer **103**, the first absorber layer **105**, and the second absorber layer **104**. In block **2512** the first photoresist layer may be removed. As shown in FIG. **24E**, after removing the first photoresist layer **189**, the metamaterial may include a void in the outer conductive layer and the absorber layers. In block **2514** a second photoresist layer may be deposited over the metamaterial. As shown in FIG. **24**F the second photoresist layer **190** covers the bristles and the void in the metamaterial created by the etching step. In block **2516** a second mask may be positioned over the second photoresist layer. As shown in FIG. **24**G, a second mask **196** may block the UV radiation to the second photoresist layer **190** except through the second mask portion **190***a*. This controls the UV radiation to the desired portion of the second photoresist layer **190**. In block **2518** the method may include exposing a UV source to the second photoresist layer through the second mask. As illustrated in FIG. **24**G, exposing only a portion of the second photoresist layer **190** to UV radiation creates a second exposed portion **190***a* within the second photoresist layer **190**. After creating the second exposed portion **190***a* within the second photoresist layer, the second mask may be subsequently removed from the metamaterial. In block **2520** the second photoresist layer may be developed. For a positive photoresist this includes removing the second exposed portion **190***a* leaving a template created by the remaining second photoresist layer **190** with pores **190***b* as shown in FIG. **24**H. In block **2522** a current conducting trace may be deposited on the metamaterial. Current conducting trace **1703** may be deposited on the inner conductive layer **107** through the second photoresist pore **190***b* as shown in FIG. **24**I. In block **2524** the second photoresist layer may be removed. As shown in FIG. **24**J, when the second photoresist layer **190** is removed, only the bristles and the current conducting trace **1703** remains. After removing the photoresist, a transparent coasting may be applied to the metamaterial covering the bristles and the deposited current conducting trace.

[0200] In another embodiment method that uses some of the same processes as in method **2500**, the steps for etching may include laser ablation using a wavelength-tuned laser to etch only the desired layers, as illustrated in FIGS. **24**K through **24**M. This may reduce the number of steps associated with the photolithographic techniques of method **2500** thereby reducing manufacturing cost. As illustrated, a wavelength-tuned laser **2401** may be used to etch desired exposing a desired portion of the metamaterial for a conductive trace. Since this technique provides a controlled etching alternative, it allows for any of the methods above to deposit current conducting traces at any point within the method steps.

[0201] As an alternative embodiment to the conductive traces described above, high conductive regions may be applied to the various metamaterials though directional deposition such as solid angle physical vapor deposition or ion source deposition. The method may include preferentially coating highly conductive regions with metal while leaving other regions with minimal coating to refrain from blocking entering photons. For example, the method may include coating the area between the vias or bristles ten times as thick as the coating along the sidewalls of the vias or bristles allowing photons to pass through the sidewalls while simultaneously creating a highly conductive region to act as a conductive trace. As another example, the method may include using a thicker conductive coating only on the side of bristles or vias that will receive less exposure to photons during operation of the completed metamaterial. To accomplish the single region deposition, the method may include angling the substrate during the deposition process so that only the desired side receives the highly conductive coating. Regardless of the exact process, the conductive regions may be applied to any of the methods listed above.

[0202] Metamaterials **200**, **300**, **400**, **1700**, **1900**, and **2100** formed by any of the processes above may be assembled into a solar panel. As briefly described above, the corrugated shape may be incorporated into an assembled solar panel as illustrated in FIGS. **26-32**. The panel assembly may include a corrugated base with panel surfaces angled at approximately 30 to 60 degrees for increasing off-axis photon absorption in metamaterials **200** with flat substrates as well as an increasing the planar bristle density without increasing shadowing, resulting in similar gains in total efficiency and power generation from metamaterials **300**, **400** with corrugated substrates. However, the total efficiencies gains are compounded when the panel assembly and metamaterials include a corrugated shape (e.g., metamaterial **300** in a corrugated solar panel assembly) because the assembled panel benefits from an increase in planar bristle density and off-axis photon absorption.

[0203] FIGS. **26-32** illustrate an embodiment solar panel **3100** with a corrugated base **2610**. Solar panels with a corrugated base **2610** may be formed by assembling metamaterials **200**, **300**, **400**, **1700**, **1900**, and/or **2100** together. FIG. **26** illustrates a perspective view of a section of a solar panel **2600**. Solar panel section **2600** may include one or more panel surfaces **2602**, **2604** in an alternating fashion on a corrugated base **2610**. In an embodiment, each panel surface **2602**, **2604** may include metamaterials **200**, **300**, **400**, **1700**, **1900**, and/or **2100** with photovoltaic bristles **201**, **301**, **401**. In an embodiment, panel surfaces **2602**, **2604** may include the same metamaterial. For example, each panel surface **2602**, **2604** may include metamaterials **200** with a flat substrate **202**. In an embodiment, panel surfaces **2602**, **2604** may include different metamaterials. For example, panel surfaces **2602** may include metamaterials **200** with flat substrates **202** while panel surfaces **2604** may include metamaterials **300** with corrugated substrates **302**. In an embodiment, a first panel surface **2602** may include metamaterials **200**, **300**, **400**, **1700**, **1900**, and/or **2100**, while a second panel surface **2604** is without metamaterial **200**, **300**, **400**, **1700**, **1900**, and/or **2100**. For example, solar panel section **2600** may include a first panel surface **2602** with metamaterials **300** alternating along a corrugated base **2610** with a second panel surface **2604** without metamaterials. In an embodiment, a second panel surface **2604** without metamaterials **200**, **300**, and/or **400** may include a reflective film (i.e., a mirror). For example, the first and second panel surfaces **2602**, **2604** may alternate along the corrugated base **2610** with a first panel surface **2602** with metamaterials **400** and a second panel surface **2604** with only a reflective film. Regardless, each panel surface **2602**, **2604** rests on the front of a corrugated base **2610**.

[0204] In an embodiment, fasteners **2612** may be used to fasten the panel surfaces **2602**, **2604** to the corrugated base **2610** with connectors **2608**. The same fastener **2612** may also fasten the rails **2902** (shown in FIG. **29**) to the corrugated base **2610** and the connectors **2608**. In an embodiment, solar panel section **2600** may include a buss bar **2606** with connectors **2608** to connect the buss bar **2606** to each metamaterial **200**, **300**, **400**, **1700**, **1900**, and/or **2100** of the panel surfaces **2602**, **2604**. In an embodiment, the buss bar **2606** may connect to the corrugated base **2610** in a slot **2614** of the corrugated based **2610**. The slot **2614** may provide stability for the buss bar **2606** as well as allow solar panel section **2600** to rest on a flat back of the corrugated base **2610**.

[0205] FIG. **27** illustrates a top view of solar panel section **2600**. As illustrated with FIG. **26**, the solar panel section **2600** may include panel surfaces **2602**, **2604**, a corrugated base **2610**, a buss bar **2606**, fasteners **2612**, and connectors **2608**.

[0206] FIG. **28** illustrates a side view of solar panel section **2600**. As illustrated, the connectors **2608** may use a single fastener **2612** for each pair of panel surfaces **2602**, **2604**. The fastener **2612** may be any means of fastening the connectors **2608** to the corrugated base **2610** and the panel surfaces **2602**, **2604**. For example, the fasteners **2612** may utilize a bolt, a joint, a rivet, screws, a pin, clips, latch, etc. In an embodiment, the fastener **2612** may be metal or metalized to create an electrical pathway from the metamaterials **200**, **300**, **400**, **1700**, **1900**, and/or **2100** of panel surfaces **2602**, **2604** to the connectors **2608**. As referenced in FIG. **26** the corrugated base **2610** may have a slot **2614** for the buss bar **2606**. The slot **2614** may allow the buss bar **2606** to connect to the backside of the corrugated base **2610** and form a flat surface (i.e. flat back) of the corrugated base **2610**. The flat surface of the backside of the corrugated base **2610** may allow for a more stable assembly for the completed solar panel **2600**.

[0207] FIG. **29** illustrates an exploded view of a solar panel section **2600**. As illustrated, rail **2902** may be secured to the corrugated base **2610** by a securing mechanism **2901**. The rail **2902** may be secured to the corrugated base **2610** by any means possible. For example, the rail **2902** may be secured to the backside of the corrugated base **2610** by a rivet, crimping, a bolt, adhesive or any other securing means. In another example, the rail **2902** may be secured to the corrugated base **2610** similar to a fastener **2612** used to fasten the panel surfaces **2602**, **2604** to the corrugated base **2610**. In an embodiment, the rail **2902** also may be fastened by the fastener **2612** to panel surfaces **2602**, **2604** on the backside of the corrugated base **2610** opposite the connectors **2608**. In an embodiment, the rail **2902** may be fastened to the panel surfaces **2602**, **2604** by any means possible including the fastening means as described with reference to FIG. **28**. In an embodiment, the buss bar **2606** may be secured to the corrugated base **2610** by a securing mechanism **2901**. In an embodiment, the buss bar **2606** may be attached to the rail **2902** with an attachment mechanism **2904**. The attachment mechanism **2904** may be any means of attachment. The attachment mechanism may be the same as the securing mechanisms **2901**, or the fasteners **2612** as described above.

[0208] In an embodiment, the rails **2902** and the buss bars **2606** may be electrically connected to the metamaterials **200**, **300**, **400**, **1700**, **1900**, and/or **2100** of panel surfaces **2602**, **2604**. In an embodiment, the rails **2902** may be electrically connected to connectors **2608**. The connectors **2608** may be electrically connected to the panel surfaces **2602**, **2604** including metamaterials **200**, **300**, **400**, **1700**, **1900**, and/or **2100**. The metamaterials **200**, **300**, **400**, **1700**, **1900**, and/or **2100** may create electron movement when the photovoltaic bristles **201**, **301**, **401** are struck by photons. In an embodiment, the outer conductive layer **103** of metamaterials **200**, **300**, **400** illustrated in FIGS. 2B, 3B, and 4B may be electrically connected to connectors **2608**. In an embodiment the current conducting traces **1701**, **1702**, **1703**, **1901**, and/or **2101** of metamaterials **1700**, **1900**, **2100** as illustrated in FIGS. **17**, **19**, and **21** may be electrically connected the connectors **2608** to help reduce the electrical resistance in the metamaterial **1700**, **1900**, **2100**. Regardless, electron movement may create electricity to flow from the metamaterials **200**, **300**, **400**, **1700**, **1900**, and/or **2100** within the panel surfaces **2602**, **2604** to the connectors **2608** to the rails **2902** and buss bars **2606** connected to the rails **2902**. From the rails **2902** and buss bars **2606**, the electricity may flow to other rails **2902** and buss bars **2606** in neighboring panel sections **2600** and eventually to an electrical destination (e.g. electrical storage) connected to the completed solar panel **3100**.

[0209] FIG. **30** illustrates a back view of a solar panel section **2600**. As discussed earlier, the buss bar **2606** of the solar panel section **2600** may have a securing mechanism **2901** to help stabilize the buss bar **2606** on the backside of the corrugated section **2600**. In an embodiment, each buss bar **2606** may have one or more securing mechanism **2901** to secure the buss bar **2606** to the back of the corrugated base **2610**. Alternatively, each buss bar **2606** may not have a securing mechanism **2901** with the corrugated base **2610** and may be secured and connected only with the rails **2902**. Although FIGS. **26-30** depict a solar panel section **2600** with two rails **2902** and two buss bars **2606**, a solar panel section **2600** may have any number of rails **2902** and buss bars **2606**. Some examples of solar panel sections **2600** with a different number of rails include solar panel sections with one rail, two rails, three rails, four rails, five rails, etc. Some other examples of solar panel sections with a different number of buss bars include panel sections with one buss bar, two buss bars, three buss bars, four buss bars, five buss bars, etc.

[0210] FIG. **31** illustrates a perspective view of a solar panel **3100** with multiple solar panel sections **2600**. In an embodiment, each solar panel section **2600** may include metamaterials **200**, **300**, **400**. In another embodiment, the metamaterials may include current conducting traces **1701**, **1702**, **1703**, **1901**, **2101** as illustrated in metamaterials **1700**, **1900**, or **2100** of FIGS. **17**, **19**, and **21**. In an embodiment, each solar panel section **2600** may be adjacent and combine with one or more other solar panel sections **2600**. In an embodiment, the solar panel **3100** may include a frame **3102** that surrounds the outer perimeter of the combined solar panel sections **2600** within the solar panel **3100**.

[0211] FIG. **32** illustrates an exploded view of a solar panel **3100**. In an embodiment, the solar panel **3100** may include a frame **3102**, a top cover **3202**, and a back cover **3208**. In an embodiment, the frame **3102** is connected with corner brackets **3206** and fasteners **3204** to the corners of solar panel sections **2600** positioned in the corners of solar panel **3100**. In an embodiment, the frame **3102** for solar panel **3100** may include two short pieces **3214***a*, **3214***b* and two long pieces **3216***a*, **3216***b* to attach along the four sides of the assembled solar panel sections **2600**. In an embodiment, the solar panel **3100** may have four or more corner brackets **3206** (e.g., eight as shown) to connect the pieces of the frame **3102** to the assembled solar panel sections **2600**.

[0212] In an embodiment, the top cover **3202** of the solar panel **3100** may be transparent or semitransparent. The top cover **3202** may protect the solar panel section **3100** and their electrical and photovoltaic components. For example, the top cover **3202** may protect the solar panel section **2600** and their electrical and photovoltaic components from oxygen corrosion, wind, water, and dirt or anything else that may reduce the efficiency or life of the metamaterials **200**, **300**, **400**, **1700**, **1900**, and/or **2100** in solar panel **3100**.

[0213] In an embodiment, the back cover **3208** of solar panel **3100** may include rounded slots **3212** so that fasteners **3210** may connect the back cover **3208** to the assembled (i.e., combined) solar panel sections **2600**. The fasteners **3210** may be any type that may connect the back cover **3208** to the assembled solar panel sections **2600**. For example, the fasteners **3210** may fasten similar to the fasteners **2612** as described with reference to FIG. **28** (e.g., by bolts, screws, etc.).

[0214] In an embodiment, the back cover **3208** and the top cover **3202** may be sealed within the solar panel **3100** by the frame **3102**. In an embodiment, only the back cover **3208** or the top cover **3202** may be sealed within the solar panel **3100** by the frame **3102**. The back cover **3208** and the top cover **3202** may provide structural support to the solar panel **3100** and its subparts. In addition, the back cover **3208** and the top cover **3202** may protect the subparts of the solar panel **3100** from any contamination that may reduce the efficiency and life of the metamaterials **200**, **300**, **400**, **1700**, **1900**, and/or **2100** in solar panel **3100** such as wind, water, dirt or oxygen, etc.

[0215] In another embodiment, the volumetric efficiency gains realized from the solar panel with the corrugated sections may be achieved by mounting completed solar panels in corrugated patterns with respect to each other. Thus, completed solar panels may be mounted in an array of solar panels where the surfaces of each solar panel form an angle of approximately 30 to 60 degrees with a common plane such as a base connecting the solar panels that is perpendicular to the sun. As an alternative embodiment, reflectors may replace some completed solar panels in the corrugated pattern to help maximize efficiency gain of each completed solar panel.

[0216] The preceding description of the disclosed embodiments is provided to enable any person skilled in the art to make or use the present invention. Various modifications to these embodiments will be readily apparent to those skilled in the art, and the generic principles defined herein may be applied to other embodiments without departing from the spirit or scope of the invention. Thus, the present invention is not intended to be limited to the embodiments shown herein but is to be accorded the widest scope consistent with the following claims and the principles and novel features disclosed herein.

What is claimed is:

1. A method for manufacturing a metamaterial, comprising:

creating a daughter template on a web from an original master template; and

imprinting a pattern from the daughter template on a moldable material positioned on a substrate using a web-to-plate printing process.

2. The method of claim **1**, wherein the pattern is an array of cores.

3. The method of claim **1**, wherein the pattern is an array of vias.

4. A system for manufacturing a solar array, comprising:

a roll-to-web subsystem configured to transfer a first pattern from a master die to a daughter die on a web;

a daughter die; and

a web-to-plate subsystem configured to imprint the daughter die onto a substrate to generate a pattern of micron-sized structures on the substrate suitable for forming a metamaterial structure of photovoltaically active bristles.

5. The system of claim **4**, wherein the pattern of micron-sized structures on the substrate comprises an array of cores on the substrate.

6. The system of claim **4**, wherein the pattern of micron-sized structures on the substrate comprises an array of vias on the substrate.

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