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(54) **RESIST SENSITIVITY AND PROFILE IMPROVEMENT VIA ACID ANION CONTROL DURING FIELD-GUIDED POST EXPOSURE BAKE**

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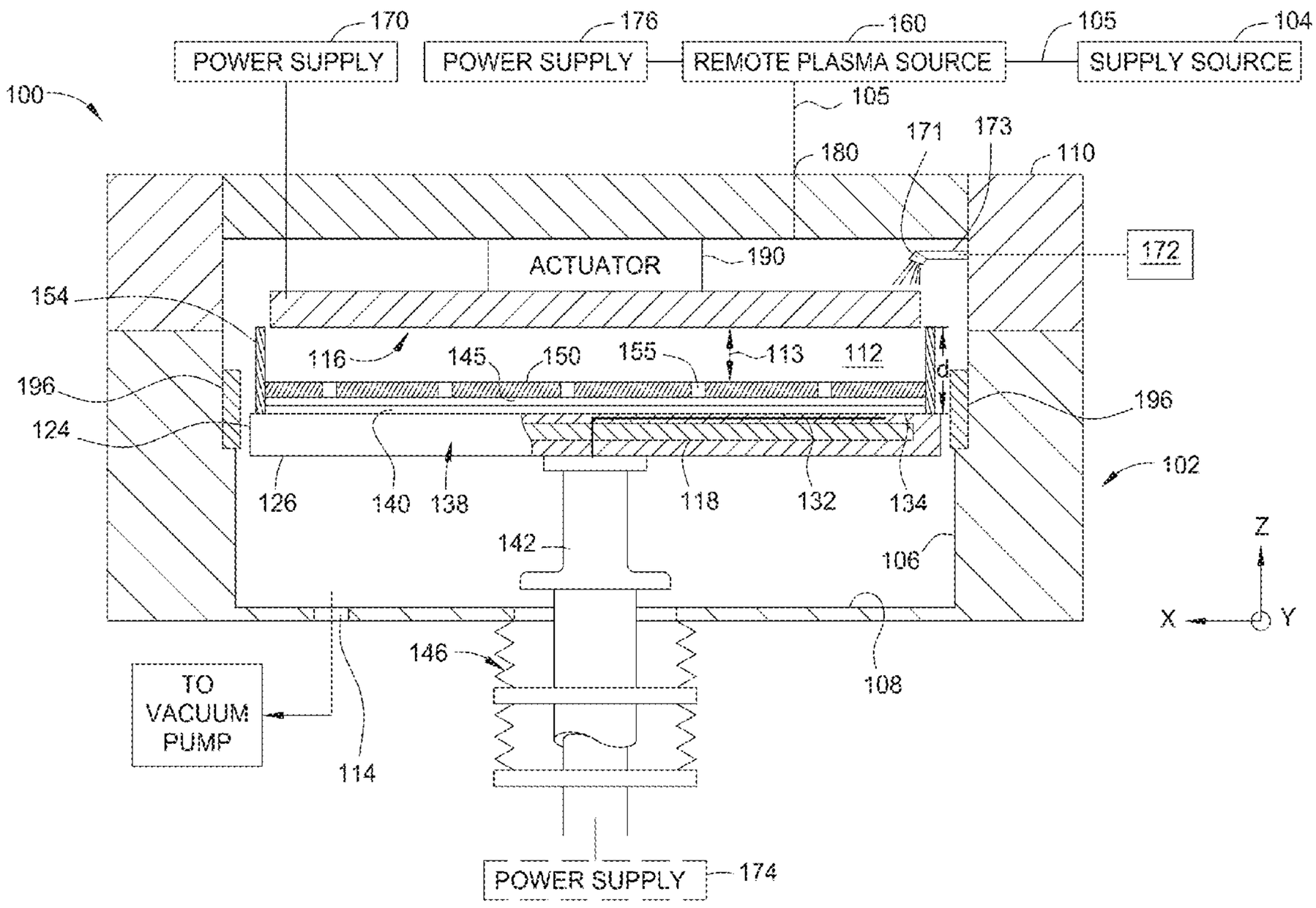
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CPC ***G03F 7/70058*** (2013.01)

(57) **ABSTRACT**

Methods disclosed herein provide apparatus and methods for applying an electric field and/or a magnetic field to a photoresist layer without air gap intervention during photolithography processes. In one embodiment, an apparatus includes a processing chamber configured to apply an electric field to a substrate via a non-gas phase intermediate medium. Methods described herein include dissociation of a photoacid generator to generate anions and cations. The anions may be moved within the photoresist layer by the electric field to more precisely control the speed and location of acid generation and regeneration processes.



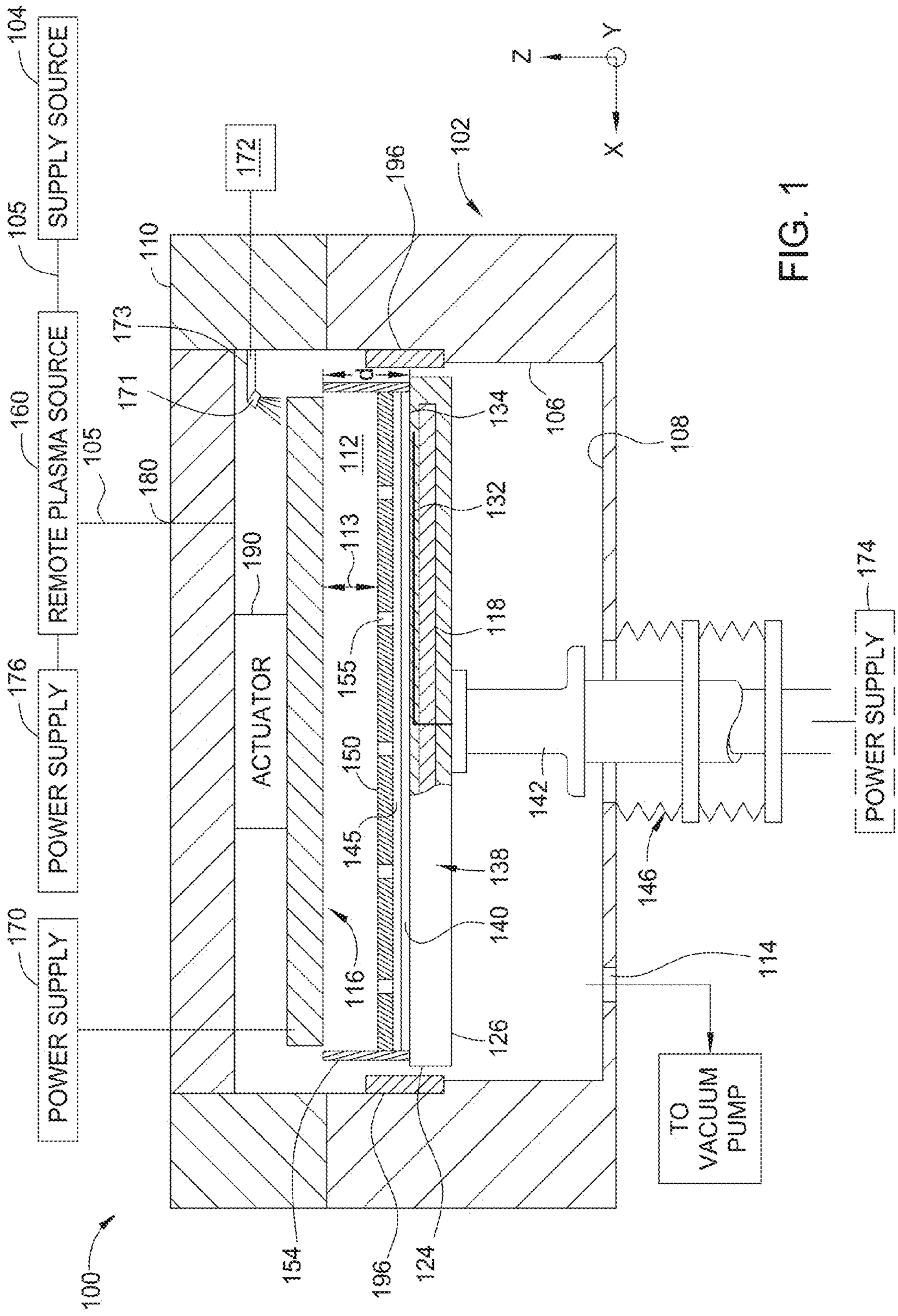

104
SUPPLY SOURCE
105
REMOTE PLASMA SOURCE
160
POWER SUPPLY
176
POWER SUPPLY
170
172
110
173
171
105
180
190
ACTUATOR
196
102
Z
Y
X
d
134
106
108
112
132
113
118
155
150
145
142
138
140
146
116
126
114
POWER SUPPLY
174
TO VACUUM PUMP
100
154
196
124

FIG. 1

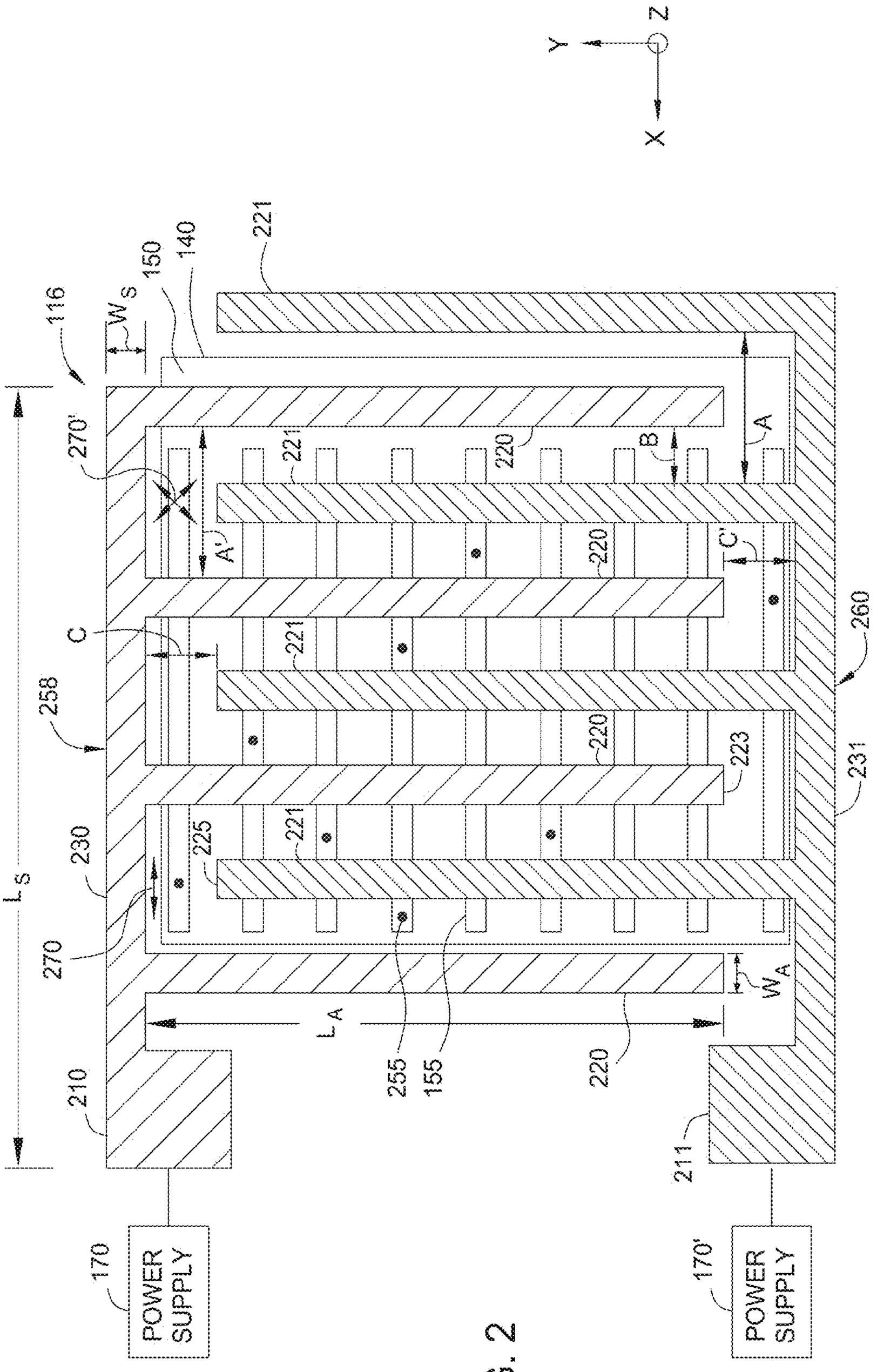

Z
Y
X
116
W_S
150
140
221
270'
220
B
A
A'
C'
C
258
260
231
230
225
223
270
L_S
L_A
W_A
255
155
210
211
170
POWER SUPPLY
170'
POWER SUPPLY

FIG. 2

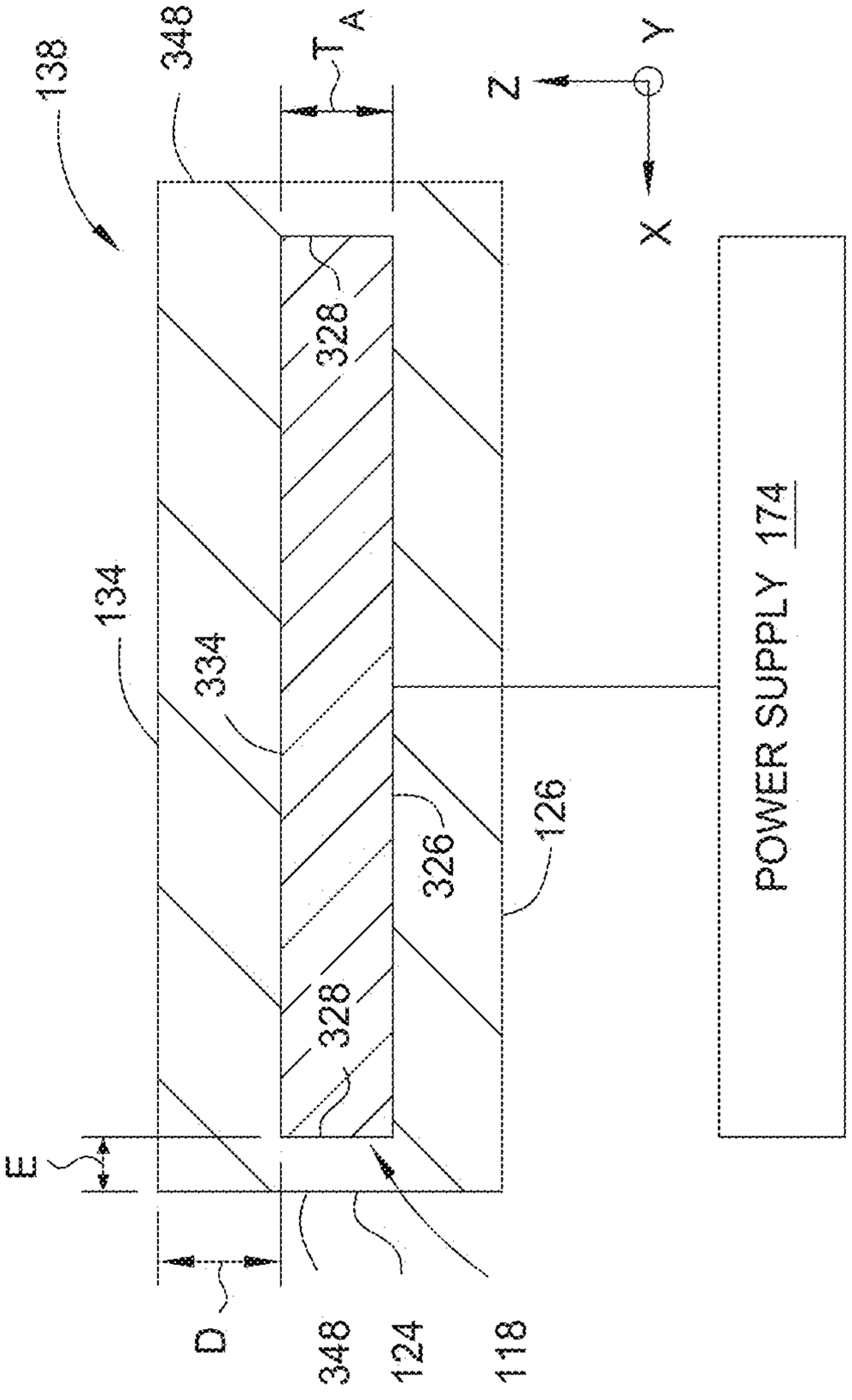

138
348
T_A
Z
Y
X
328
134
334
326
126
328
POWER SUPPLY 174
E
D
348
124
118

FIG. 3

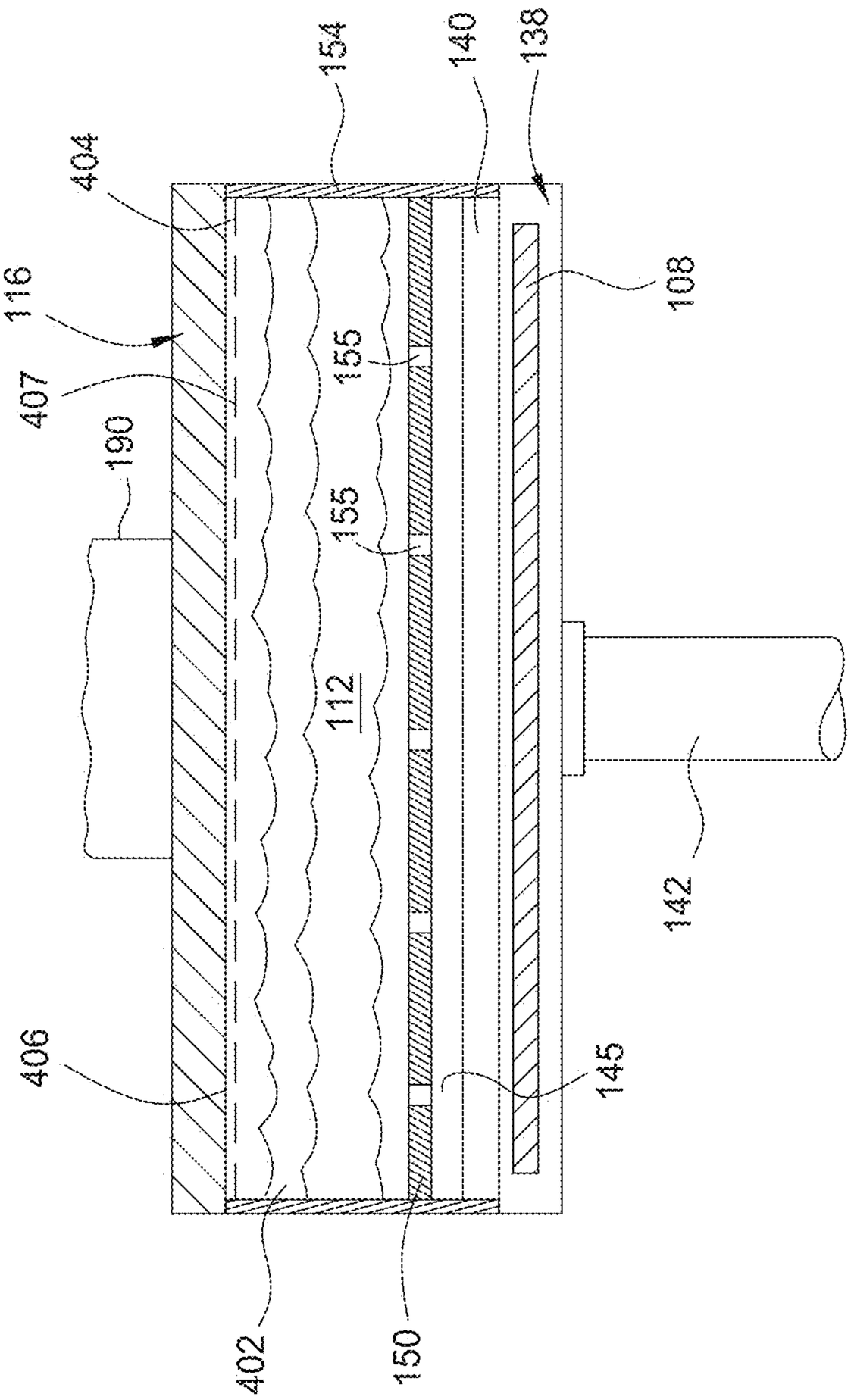


FIG. 4A

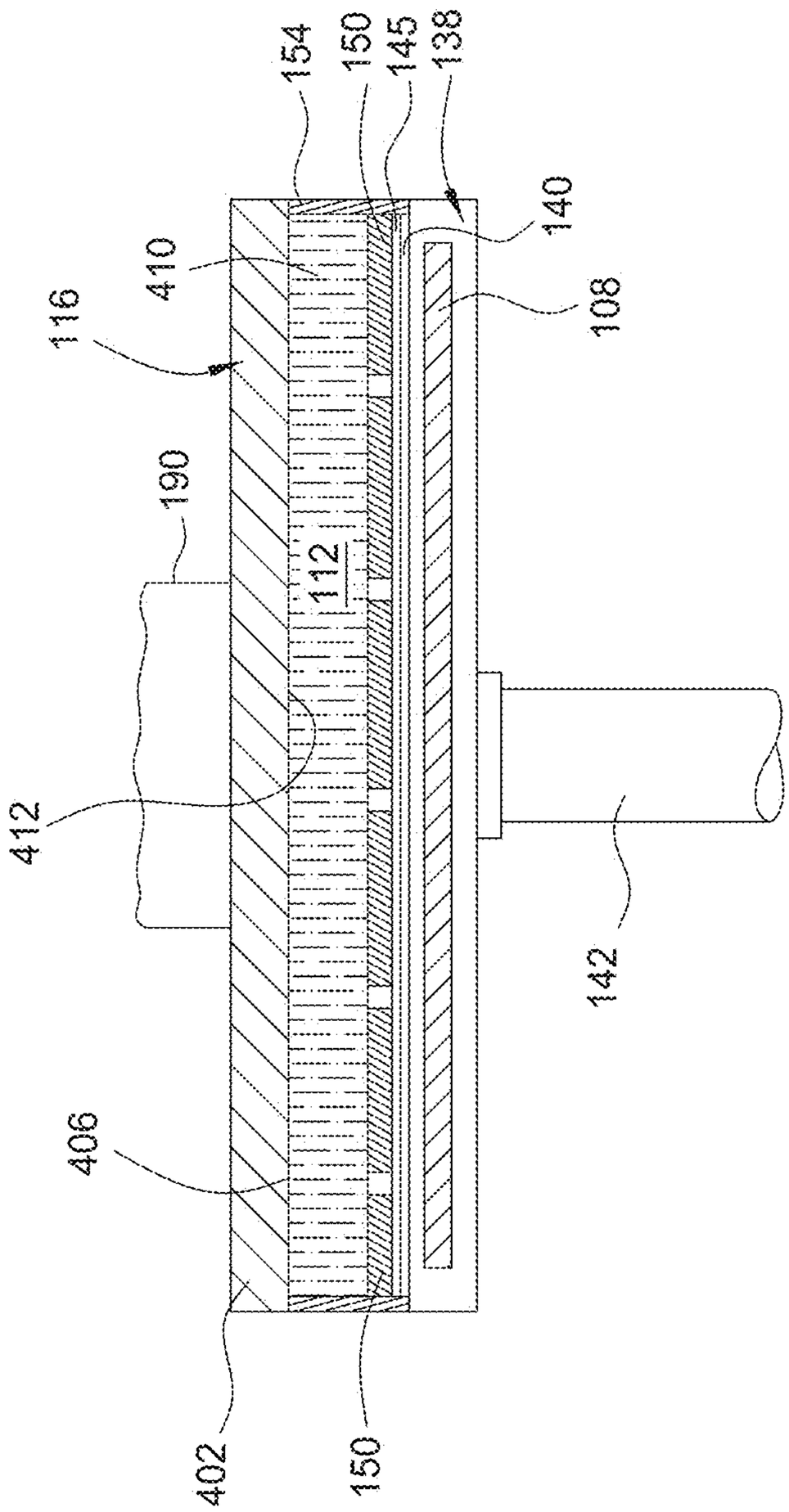


FIG. 4B

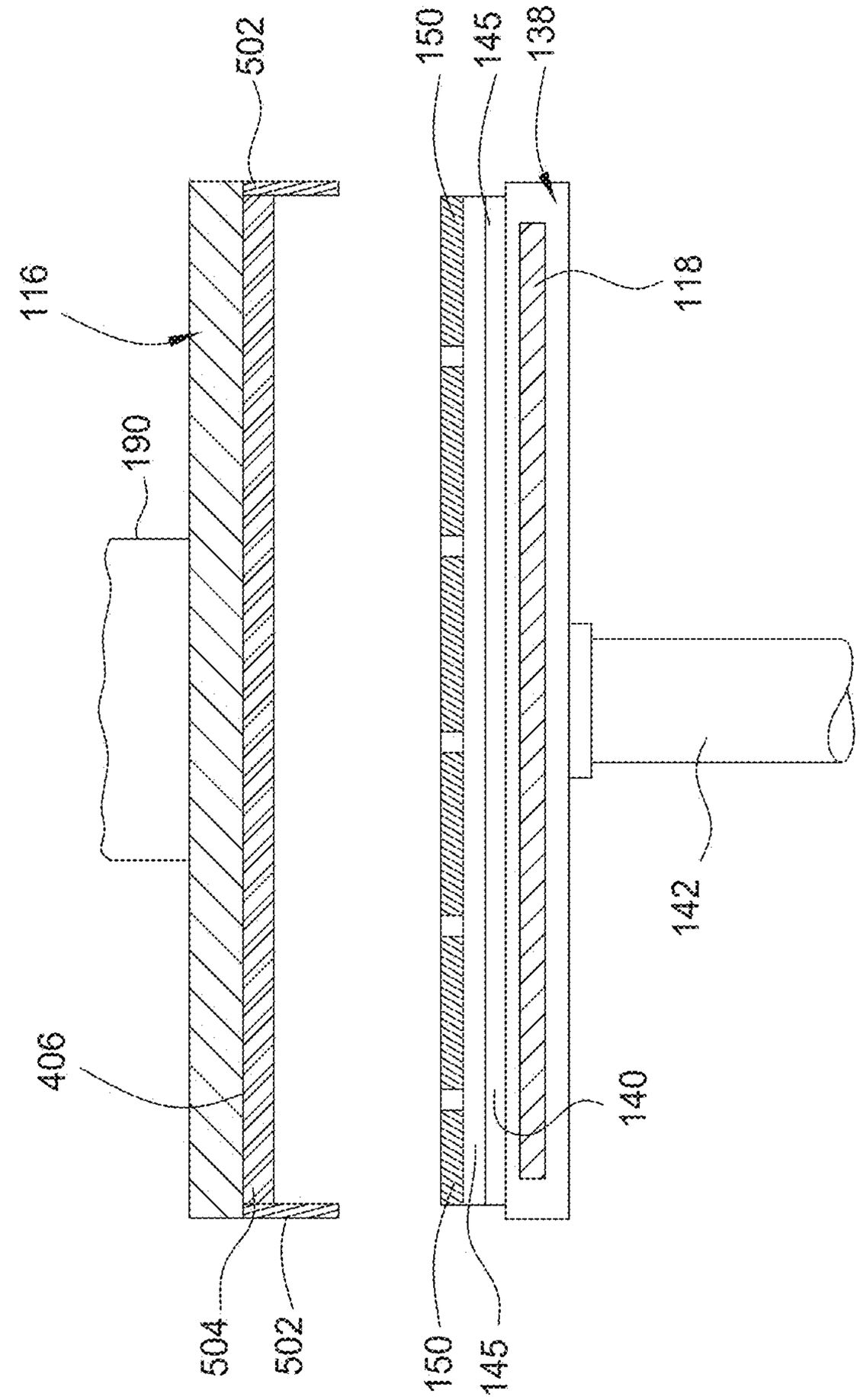


FIG. 5A

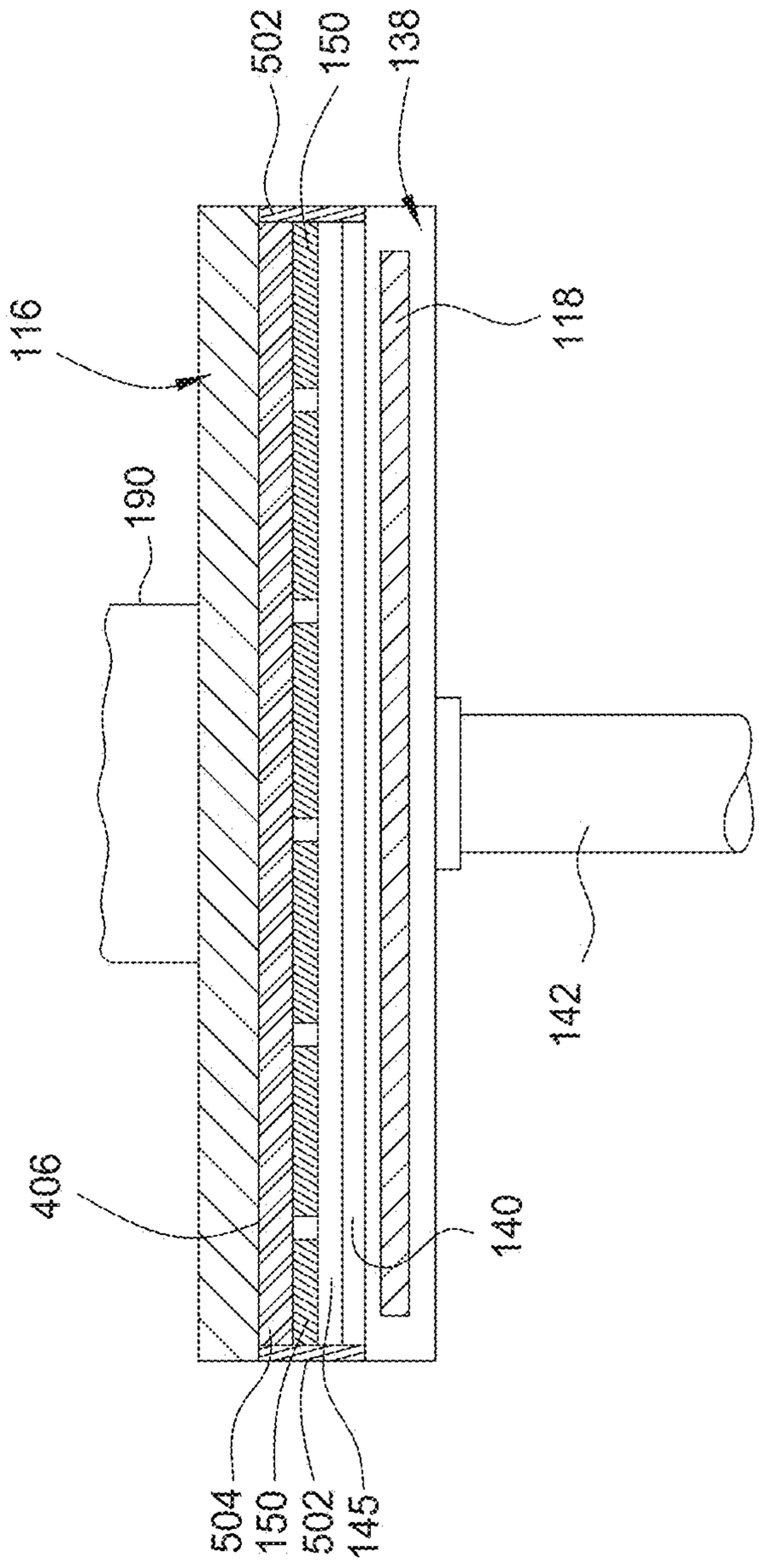


FIG. 5B

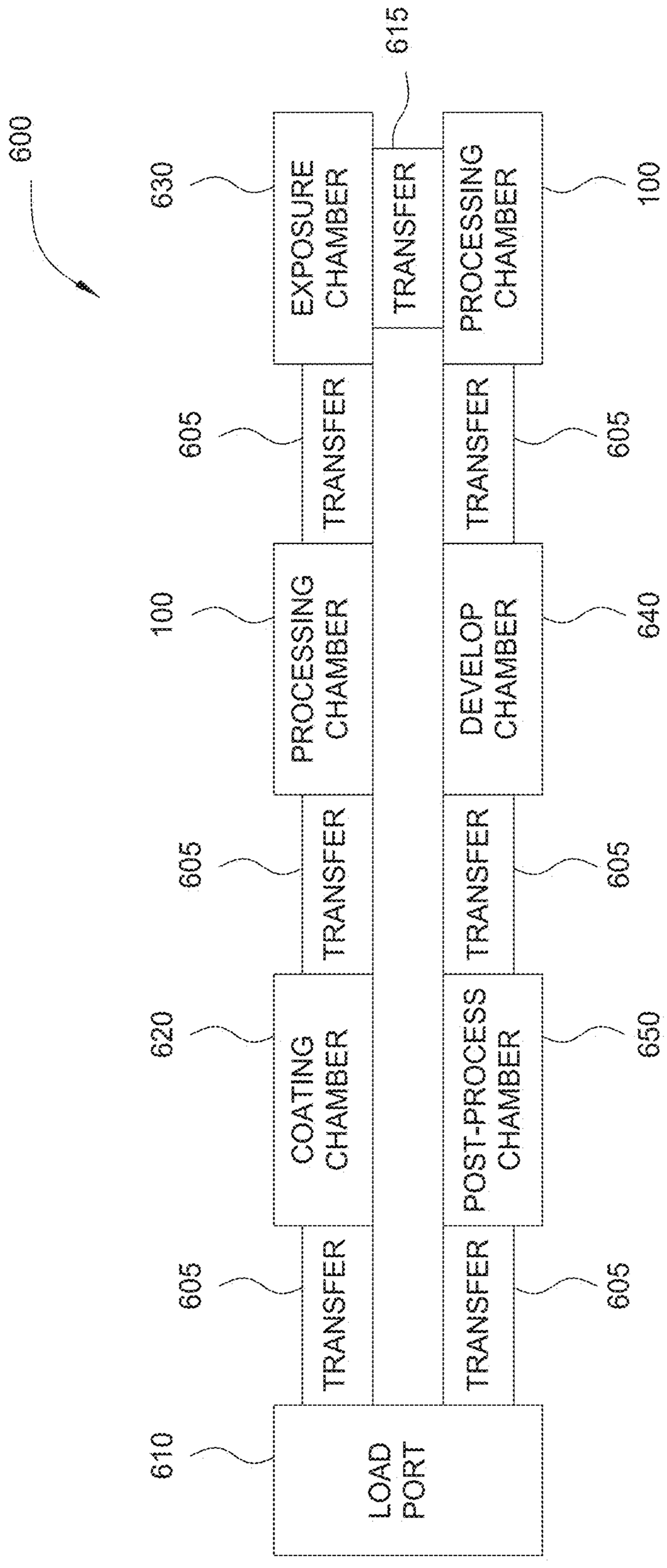

600
630
EXPOSURE CHAMBER
615
TRANSFER
PROCESSING CHAMBER
100
605
TRANSFER
605
TRANSFER
100
PROCESSING CHAMBER
DEVELOP CHAMBER
640
605
TRANSFER
605
TRANSFER
620
COATING CHAMBER
POST-PROCESS CHAMBER
650
605
TRANSFER
605
TRANSFER
610
LOAD PORT

FIG. 6

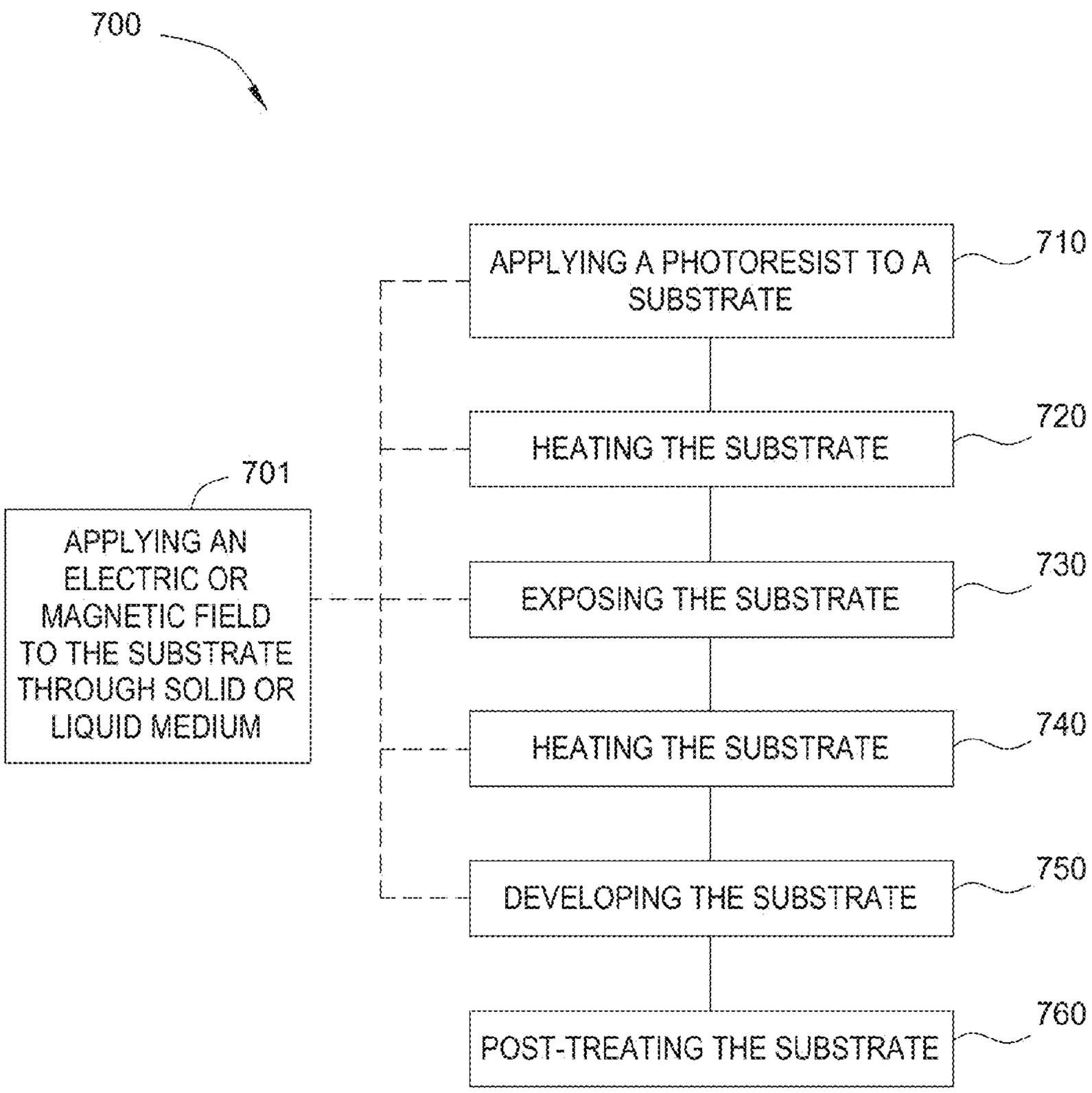

700
APPLYING A PHOTORESIST TO A SUBSTRATE
710
HEATING THE SUBSTRATE
720
701
APPLYING AN ELECTRIC OR MAGNETIC FIELD TO THE SUBSTRATE THROUGH SOLID OR LIQUID MEDIUM
EXPOSING THE SUBSTRATE
730
HEATING THE SUBSTRATE
740
DEVELOPING THE SUBSTRATE
750
POST-TREATING THE SUBSTRATE
760

FIG. 7

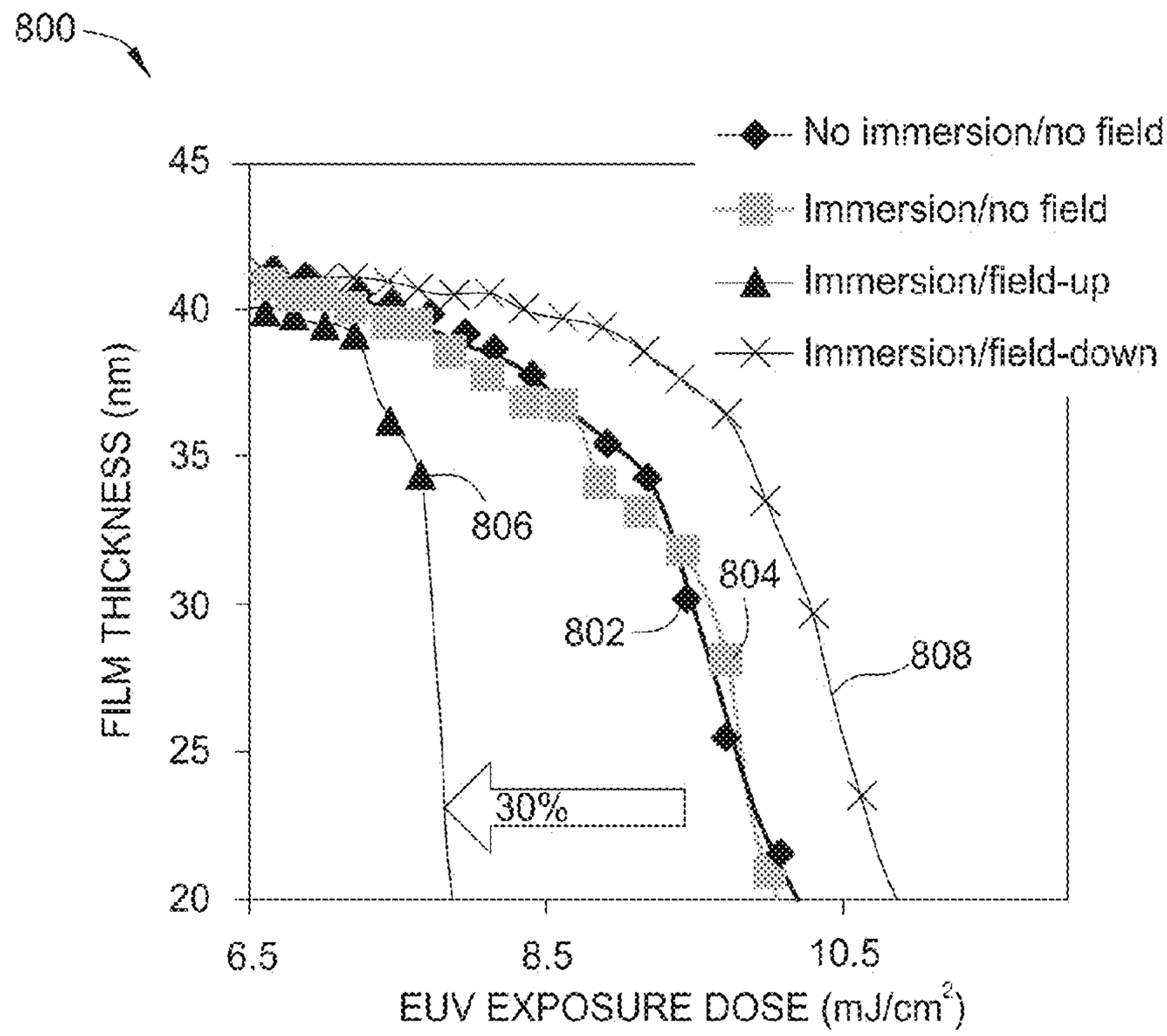

800
No immersion/no field
Immersion/no field
Immersion/field-up
Immersion/field-down
45
40
35
30
25
20
FILM THICKNESS (nm)
806
804
802
808
30%
6.5
8.5
10.5
EUV EXPOSURE DOSE (mJ/cm²)

FIG. 8

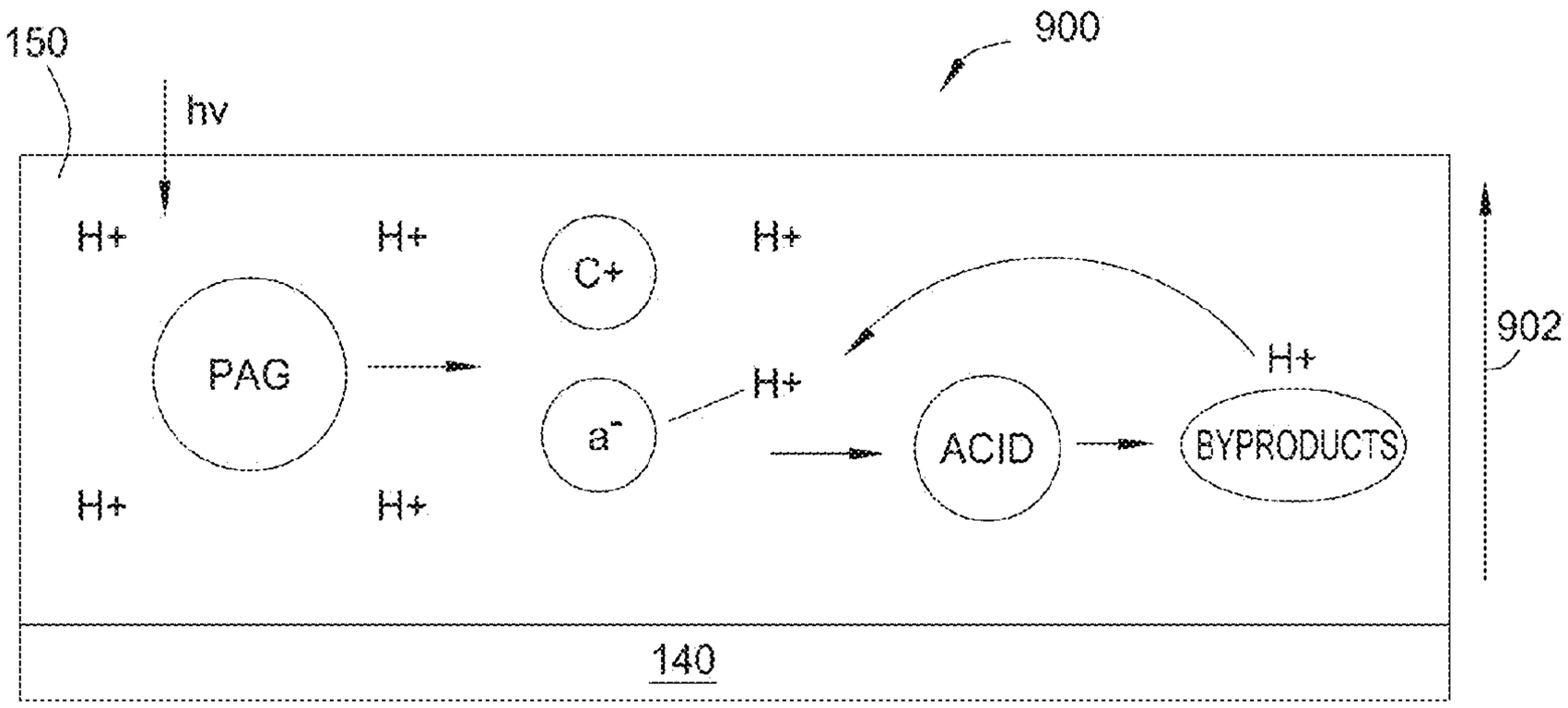

150
hv
900
H+
H+
H+
C+
PAG
a⁻
H+
H+
H+
H+
ACID
BYPRODUCTS
902
140

FIG. 9

RESIST SENSITIVITY AND PROFILE IMPROVEMENT VIA ACID ANION CONTROL DURING FIELD-GUIDED POST EXPOSURE BAKE

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] This application claims benefit to U.S. Provisional Patent Application No. 62/236,655, filed Oct. 2, 2015, the entirety of which is herein incorporated by reference.

BACKGROUND

[0002] Field

[0003] The present disclosure generally relates to methods and apparatus for processing a substrate, and more specifically to methods and apparatus for improving photolithography processes.

[0004] Description of the Related Art

[0005] Integrated circuits have evolved into complex devices that can include millions of components (e.g., transistors, capacitors and resistors) on a single chip. Photolithography is a process that may be used to form components on a chip. Generally the process of photolithography involves a few basic stages. Initially, a photoresist layer is formed on a substrate. A chemically amplified photoresist may include a resist resin and a photoacid generator. The photoacid generator, upon exposure to electromagnetic radiation in the subsequent exposure stage, alters the solubility of the photoresist in the development process. The electromagnetic radiation may have any suitable wavelength, for example, a 193 nm ArF laser, an electron beam, an ion beam, or other suitable source. Excess solvent may then be removed in a pre-exposure bake process.

[0006] In an exposure stage, a photomask or reticle may be used to selectively expose certain regions of the substrate to electromagnetic radiation. Other exposure methods may be maskless exposure methods. Exposure to light may decompose the photo acid generator, which generates acid and results in a latent acid image in the resist resin. After exposure, the substrate may be heated in a post-exposure bake process. During the post-exposure bake process, the acid generated by the photoacid generator reacts with the resist resin, changing the solubility of the resist during the subsequent development process.

[0007] After the post-exposure bake, the substrate, and, particularly, the photoresist layer may be developed and rinsed. Depending on the type of photoresist used, regions of the substrate that were exposed to electromagnetic radiation may either be resistant to removal or more prone to removal. After development and rinsing, the pattern of the mask is transferred to the substrate using a wet or dry etch process.

[0008] The evolution of chip design continually requires faster circuitry and greater circuit density. The demands for greater circuit density necessitate a reduction in the dimensions of the integrated circuit components. As the dimensions of the integrated circuit components are reduced, more elements are required to be placed in a given area on a semiconductor integrated circuit. Accordingly, the lithography process must transfer even smaller features onto a substrate, and lithography must do so precisely, accurately, and without damage. In order to precisely and accurately transfer features onto a substrate, high resolution lithography may use a light source that provides radiation at small wavelengths. Small wavelengths help to reduce the minimum printable size on a substrate or wafer. However, small wavelength lithography suffers from problems, such as low throughput, increased line edge roughness, and/or decreased resist sensitivity.

[0009] In a recent development, an electrode assembly is utilized to generate an electric field to a photoresist layer disposed on the substrate prior to or after an exposure process so as to modify chemical properties of a portion of the photoresist layer where the electromagnetic radiation is transmitted to for improving lithography exposure/development resolution. However, the challenges in implementing such systems have not been.

[0010] Therefore, there is a need for improved methods and apparatus for improving photolithography processes.

SUMMARY

[0011] In one embodiment, a photolithography method is provided. The method includes exposing a substrate having a photoresist layer disposed thereon to electromagnetic radiation. The photoresist layer may include a photoacid generator and the photoresist layer may be ionized. The method also includes dissociating the photoacid generator to form anions and cations in a first resist region and facilitating acid generation by protonating the anions in the first resist region by applying an electromagnetic field to the substrate to move the anions within the photoresist layer to a second resist region. In addition, the method includes facilitating acid generation by protonating the anions in the second resist region.

[0012] In another embodiment, a photolithography method is provided. The method includes exposing a substrate having a photoresist layer disposed thereon to extreme ultraviolet radiation. The photoresist layer may include a photoacid generator and the photoresist layer may be ionized. The method also includes dissociating the photoacid generator to for anions and cations in a first resist region adjacent an exposed surface of the photoresist layer, heating the substrate and the photoresist layer, and facilitating acid generation by protonating the anions in the first resist region. Applying an electromagnetic filed to the substrate is performed via a non-gas phase medium to move the anions within the photoresist layer to a second resist region different than the first resist region. The method also includes facilitating acid generation by protonating the anions in the second resist region.

[0013] In yet another embodiment, a substrate processing method is provided. The method includes applying a photoresist to a substrate in a first processing chamber and transferring the substrate via a first transfer chamber to a second processing chamber. The substrate is heated in the second processing chamber and the substrate is transferred via a second transfer chamber to a third processing chamber. The substrate is exposed to extreme ultraviolet radiation in the third processing chamber and the substrate is transferred via a third transfer chamber to a fourth processing chamber. The second processing chamber and the fourth processing chamber may be configured similarly and an electric field may be applied to the substrate via a non-gas phase medium to cause movement of anions within the photoresist in the fourth processing chamber. The substrate is transferred via a fourth transfer chamber to a fifth processing chamber where the photoresist on the substrate is developed.

BRIEF DESCRIPTION OF THE DRAWINGS

[0014] So that the manner in which the above recited features of the present disclosure can be understood in detail, a more particular description of the disclosure, briefly summarized above, may be had by reference to embodiments, some of which are illustrated in the appended drawings. It is to be noted, however, that the appended drawings illustrate only typical embodiments of this disclosure and are therefore not to be considered limiting of its scope, for the disclosure may admit to other equally effective embodiments.

[0015] FIG. **1** illustrates a schematic cross-sectional view of an apparatus for processing a substrate according to one embodiment described herein.

[0016] FIG. **2** illustrates a top view of embodiment of an electrode assembly of apparatus of FIG. **1** according to one embodiment described herein.

[0017] FIG. **3** illustrates a schematic, side cross-sectional view of one embodiment of the substrate support assembly of FIG. **1** having an electrode assembly embedded therein according to one embodiment described herein.

[0018] FIGS. **4**A-**4**B are schematic illustrations representative of an intermediate medium that may be used to process a substrate according to embodiments disclosed herein.

[0019] FIGS. **5**A-**5**B are schematic illustrations representative of an intermediate medium that may be used to process a substrate according to embodiments disclosed herein.

[0020] FIG. **6** illustrates a schematic illustration of one representative cluster processing system that may be used to process a substrate according to embodiments disclosed herein.

[0021] FIG. **7** illustrates a flow diagram of a method of processing a substrate according to one embodiment described herein.

[0022] FIG. **8** is a graph illustrating dose sensitivity of a photoresist according to embodiments described herein.

[0023] FIG. **9** schematically illustrates a mechanism of acid regeneration in a photoresist according to embodiments described herein.

[0024] To facilitate understanding, identical reference numerals have been used, wherever possible, to designate identical elements that are common to the Figures. Additionally, elements of one embodiment may be advantageously adapted for utilization in other embodiments described herein.

DETAILED DESCRIPTION

[0025] Methods and apparatus for minimizing line edge/width roughness and improving exposure resolution in a photolithography process for semiconductor applications are provided. The methods and apparatuses disclosed herein may increase the photoresist sensitivity and productivity of photolithography processes. The random diffusion of acids generated by a photoacid generator during a post-exposure bake procedure contributes to line edge/width roughness and reduced resist sensitivity. An electrode assembly may be utilized to apply an electric field and/or a magnetic field to the photoresist layer during photolithography processes. The field application may control the diffusion of the charged species generated by the photoacid generator.

[0026] An air gap defined between the photoresist layer and the electrode assembly may result in voltage drop applied to the electrode assembly, thus, adversely lowering the level of the electric field desired to be generated to the photoresist layer. As a result of the voltage drop, levels of the electric field at the photoresist layer may result in insufficient or inaccurate voltage power to drive or create charged species in the photoresist layer in certain desired directions. Thus, diminished line edge profile control to the photoresist layer may prevalent.

[0027] An intermediate medium may be disposed between the photoresist layer and the electrode assembly to prevent the air gap from being created so as to maintain the level of the electric field interacting with the photoresist layer at a certain desired level. By doing so, the charged species generated by the electric field may be guided in a desired direction along the line and spacing direction, preventing the line edge/width roughness that results from inaccurate and random diffusion. Accordingly, a controlled or desired level of electric field as generated may increase the accuracy and sensitivity of the photoresist layer to exposure and/or development process. In one example, the intermediate medium may be non-gas phase medium, such as a slurry, gel, liquid solution or a solid state medium that may efficient maintain voltage level as applied at a determined range when transmitting from the electrode assembly to the photoresist layer disposed on the substrate.

[0028] FIG. **1** illustrates a schematic, cross-sectional view of an substrate processing chamber **100**. In one embodiment, the processing chamber **100** is a vacuum processing chamber. In other embodiments, the processing chamber **100** may not be coupled to a vacuum source and may be operated at predominantly atmospheric pressures. The processing chamber **100** may be an independent processing chamber or may be part of a processing system, such as, for example, an in-line processing system, a cluster processing system, or a track processing system such as shown in FIG. **6** discussed further below.

[0029] The processing chamber **100** includes a chamber body **102**, an electrode assembly **116**, and a substrate support assembly **138**. The chamber walls **102** include sidewalls **106**, a lid assembly **110**, and a bottom **108**. The chamber body **102** at least partially (or entirely) encloses a processing volume **112**. The processing volume **112** is accessed through a substrate transfer port (not shown) formed through the chamber body **102**. The substrate transfer port is configured to facilitate movement of a substrate **140** into and out of the processing volume **112** of the processing chamber **100**. In embodiments where the processing chamber **100** is part of a processing system, the substrate transfer port may allow for the substrate **140** to be transferred to and from a transfer chamber.

[0030] A pumping port **114** is disposed through the chamber body **102** to couple the processing volume **112** to a pumping system. The pumping system includes various vacuum pumping and flow control components, such as a vacuum pump and throttle valve. The pumping components may reduce the pressure of the processing volume **112** and exhaust any gases and/or process by-products out of the processing chamber **100**.

[0031] The substrate support assembly **138** is centrally disposed within the processing chamber **100**. The substrate support assembly **138** supports the substrate **140** during processing. The substrate support assembly **138** may com-

prise a body **124** that encapsulates an optional electrode assembly **118**. The body **124** may comprise, for example, a metal, such as aluminum, or a ceramic material. In embodiments where the body **124** comprises a metal, the electrode assembly **118** may be encapsulated within an insulating material (not shown) that insulates the electrode assembly **118** from the metal body **124**. The electrode assembly **118** may be coupled to a power supply **174**. In other embodiments, the electrode assembly **118** may be coupled to ground. In some embodiments, the electrode assembly **118** is configured to generate an electric field parallel to the x-y plane defined by a first surface **134** of the substrate support assembly **138**. For example, the electrode assembly **118** may be configured to generate an electric field in one of the y direction, x direction or other direction in the x-y plane. In other embodiments, the electrode assembly **118** is configured to generate an electric field perpendicular to the x-y plane defined by the first surface **134** of the substrate support assembly **138**.

[0032] The substrate support assembly **138** also has a second surface **126** that is opposite the first surface **134**. The first surface **134** is configured to support the substrate **140**. The second surface **126** is coupled by a stem **142** to an actuator (not shown), which may be configured move the substrate **140** to and from a processing position. The first surface **134** of the substrate support assembly **138** is configured to support the substrate **140** during processing.

[0033] The substrate **140** may be any type of substrate, such as a dielectric substrate, a glass substrate, a semiconductor substrate, or a conductive substrate. The substrate **140** may have a layer **145** disposed thereon. The layer **145** may be any desired layer and the substrate **140** may have more than one layer **145** disposed therein. Generally, the layer **145** may include semiconductor device features, components, and precursors thereof. The substrate **140** also has a photoresist layer **150** disposed over the layer **145**.

[0034] The substrate **140** may have been previously exposed to electromagnetic radiation in an exposure stage of a photolithography process. In one embodiment, the substrate **140** may be exposed to electromagnetic radiation in a separate chamber or the processing chamber **100**. The photoresist layer **150** generally has latent image lines **155** formed therein as a result of the exposure stage. The latent image lines **155** may be substantially parallel. In other embodiments, the latent image lines **155** may not be substantially parallel, such as perpendicular or the like depending on a desired device architecture.

[0035] In some embodiments, the substrate support assembly **138** may be an electrostatic chuck. In some embodiments, the body **124** of the substrate support assembly **138** may encapsulate an embedded heater **132**. The embedded heater **132**, such as a resistive element, is disposed in the substrate support assembly **138**. The embedded heater **132** controllably heats the substrate support assembly **138** and the substrate **140** positioned thereon to a predetermined temperature. The embedded heater **132** is configured to quickly ramp the temperature of the substrate **140** and to control the temperature of the substrate **140**. In some embodiments, the embedded heater **132** is connected to and controlled by the power supply **174**. The power supply **174** may be configured similarly to the power supply **170**, as discussed below.

[0036] In some embodiments, the processing chamber **100** may include other heating sources. For example, heat lamps may be positioned within or outside the processing chamber **100**. In some embodiments, one or more lasers may be used to heat the photoresist layer **150** (or other layer) positioned on the substrate **140** or the antennas **220**, **221** of the electrode assembly **116** (shown in FIG. **2**). In some embodiments, the substrate support assembly **138** may be configured to circulate a high efficiency heat transfer fluid in order to more quickly increase the temperature of the substrate **140** positioned on the substrate support assembly **138**.

[0037] In some embodiments, the substrate support assembly **138** may be configured to provide relative motion between the first surface **134** (and the substrate **140** positioned thereon) and the electrode assembly **116**. For example, the substrate support assembly **138** may be configured to rotate about the z-axis. The substrate support assembly **138** may be configured to continuously rotate, or the substrate support assembly **138** may be configured to rotate in a step-wise manner. For example, the substrate support assembly **138** may rotate a predetermined amount of degrees about a centerline of the substrate support assembly **138**, such as about 90°, about 180°, or about 270°. The rotation may be stopped for a predetermined amount of time at any stage of the rotation. After the predetermined amount of time, the rotation may continue in a step-wise manner or in a continuous manner.

[0038] The substrate support assembly **138** may be configured to move vertically (i.e., in the z-direction). The substrate support assembly **138** may also be separated from the electrode assembly **116**. For example, the substrate support assembly **138** and the electrode assembly **116** may be separated by a distance of at least about 0.1 mm. A confinement ring **154** is disposed on an edge of the substrate support assembly **138** circumscribing the substrate support assembly **138** defining a distance d in the z-direction between the first surface **134** of the substrate support assembly **138** and the electrode assembly **116**. The confinement ring **154** may assist maintaining the substrate **140** positioned at a desired location on the first surface **134** of the substrate support assembly **138**.

[0039] The confinement ring **154** may also confine an intermediate medium, i.e., a non-gas phase medium, such as solid slurry, a gel and/or liquid medium, disposed in the processing volume **112** above the photoresist layer **150**. In one example, the confinement ring **154** may have a length, i.e., the defined distance d, between about 0.5 mm and about 10 mm, sufficient to retain the intermediate medium at a level that covers an entire surface of the photoresist layer **150** disposed on the substrate **140** when the intermediate medium is disposed in the processing volume **112**. Alternatively, the confinement ring may be disposed on an edge of the electrode assembly **116** and extend toward an edge of the substrate support assembly **138** to assist positioning of the substrate **140**. In one example, the confinement ring **154** may be manufactured from a ceramic material, conductive material, dielectric material, or other suitable material that is chemically inert to the intermediate medium.

[0040] In one example, an intermediate medium dispensing tool **173** is disposed through the chamber body **102** and into the processing chamber **100**. The intermediate medium dispensing tool **173** generally includes a nozzle **171** configured to dispense intermediate medium to the region of the processing volume **112** confined by the confinement ring **154** above the substrate **140**. The intermediate medium dispensing tool **173** is coupled to an intermediate medium

source **172**. Suitable examples of the intermediate medium includes any suitable liquid, such as water, organic gel, organic resin, organic slurry, organic solution, inorganic solution, inorganic gel, slurry, or the like, or any solid material that may be easily melted and later re-solidified to cover substantially an entire surface of the substrate **140**. Generally, the intermediate medium may be a material with a dielectric constant greater than the dielectric constant of air. Details regarding the intermediate medium that may be used will be described later with reference to FIGS. **4**A-**5**B.

[0041] The stem **142** is coupled to a lift system (not shown) for moving the substrate support assembly **138** between an elevated processing position (as shown) and a lowered substrate transfer position. In some embodiments, the lift system may also be configured to move the substrate **140** in the x-direction, the y-direction, or the x-direction and the y-direction. The stem **142** additionally provides a conduit for electrical and thermocouple leads between the substrate support assembly **138** and other components of the processing chamber **100**. A bellows **146** is coupled to the substrate support assembly **138** to provide a vacuum seal between the processing volume **112** and the atmosphere outside the processing chamber **100**, and facilitate movement of the substrate support assembly **138** in the z-direction.

[0042] The lid assembly **110** may optionally include an inlet **180** through which gases provided by supply sources **104** may enter the processing chamber **100**. The supply sources **104** may optionally controllably pressurize the processing volume **112** with a gas, such as nitrogen, argon, helium, hydrogen, neon, chlorine, other gases, or combinations thereof. The gases from the supply sources **104** may create a controlled environment (i.e. desired concentrations of various gases) within the processing chamber **100**. In other embodiments, the gases from the supply sources **104** may be used to generate a plasma. For example, the plasma may be generated in a remote plasma source **160**. The supply sources **104** may couple directly to the processing volume **112** through a supply conduit **105**. In some embodiments, the one or more source compounds may indirectly flow into the processing volume **112**. As shown, the one or more source compounds first flow through the remote plasma source **160** before flowing into the processing volume **112**.

[0043] The remote plasma source **160** may be configured to provide charged species, such as electrons, ions, radicals or the like, into the processing volume **112**. The remote plasma source may be, for example, a capacitively coupled plasma source or an inductively coupled source. The remote plasma source **160** is coupled to a power supply **176** which may be, for example, an RF power supply. The power supply **176** may be configured to deliver power at a frequency of 10 Hz and about 1 MHz, such as about 5 kHz. In other embodiments, the power supply **176** may be configured to deliver power at 13.56 MHz. The power supply **176** and the remote plasma source **160** may be configured to generate a "soft" plasma. For example, the generated plasma may contain charged species having an ion energy of between about 1 eV and about 1000 eV, such as between about 5 eV and about 50 eV. In some embodiments, the ion energy may be between about 1 eV and about 5 eV. Electrons in the soft plasma may be used to drive the charged species **255** (shown in FIGS. **2**A and **2**B) generated from the photoacid generator in a direction perpendicular to the plane of the first surface **134**. Driving the charged species in the z-direction may increase resist sensitivity.

[0044] In a representative example using a 300 mm substrate, the soft plasma may be generated as follows. It is contemplated that the gas flows may be scaled proportionately to the substrate diameter. Hydrogen gas may be provided into the remote plasma source **160** at a flow rate of between about 10 sccm and about 1000 sccm. Argon may optionally be flowed into the remote plasma source **160** at a flow rate of up to about 1000 sccm. A plasma may be generated in the remote plasma source **160** from inductively coupled RF power of between about 400 W and about 800 W. The pressure of the processing volume **112** may reduced to at least 10^{-5} Torr. For example, the pressure may be reduced to between about 10^{-6} Torr and about 10^{-8} Torr. The temperature of the substrate support assembly **138** may be maintained from room temperature to about 200° C., such as between about 70° C. and about 160° C., for example between about 90° C. and 140° C. as needed.

[0045] An actuator **190** may be coupled between the lid assembly **110** and the electrode assembly **116** to provide relative motion between the electrode assembly **116** and the substrate support assembly **138**. The actuator **190** may be configured to move the electrode assembly **116** in one or more of the x, y, and z directions. The x and y directions are referred to herein as the lateral directions or dimensions. The actuator **190** enables the electrode assembly **116** to scan the surface of the substrate **140**. The actuator **190** also enables the distance d to be adjusted. In some embodiments, the electrode assembly **116** is coupled to the lid assembly **110** by a fixed stem (not shown). In some embodiments, the actuator **190** is configured to rotate the electrode assembly **116** about z-axis. In other embodiments, the electrode assembly **116** may be coupled to the inside of the bottom **108** of the processing chamber **100**, to the second surface **126** of the substrate support assembly **138**, or to the stem **142**.

[0046] The electrode assembly **116** generally includes one or more electrodes. The electrode assembly **116** is coupled to the power supply **170**. In embodiments where the electrode assembly **116** includes more than one electrode, each electrode may be connected to a separate power supply. In some embodiments, the electrode assembly **116** is configured to generate an electric field parallel to the x-y plane defined by the first surface **134** of the substrate support assembly **138**. For example, the electrode assembly **116** may be configured to generate an electric field in one of the y direction, x direction or other direction in the x-y plane. In one embodiment, the electrode assembly **116** is configured to generate an electric field in the x-y plane and in the direction of the latent image lines **155**. In another embodiment, the electrode assembly **116** is configured to generate an electric field in the x-y plane and perpendicular to the direction of the latent image lines **155**. The electrode assembly **116** may additionally or alternatively be configured to generate an electric field in the z-direction, such as, for example, perpendicular to the first surface **134**.

[0047] The power supply **170** and/or the power supply **174** may be configured to supply, for example, between about 1 V and about 100 kV to one or more electrodes of the electrode assembly **116** and/or the electrode assembly **118**. In one embodiment, the power supply may be configured to generate an electric field having a voltage potential between about 40 V and about 4,000 V. In some embodiments, the

power supply **170** and/or the power supply **174** are a continuous or pulsed direct current (DC) power supply or a continuous or pulsed AC power. The pulsed DC wave or AC wave may be from a half-wave rectifier or a full-wave rectifier. The power supply **170** and/or the power supply **174** may be configured to provide power at a frequency of between about 10 Hz and about 1 MHz, such as about 5 kHz. The duty cycle of the pulsed DC power or AC power may be between about 5% and about 95%, such as between about 20% and about 60%. In some embodiments, the duty cycle of the pulsed DC power or AC power may be between about 20% and about 40%. In other embodiments, the duty cycle of the pulsed DC power or AC power may be about 60%.

[0048] The rise and fall time of the pulsed DC power or AC power may be between about 1 ns and about 1000 ns, such as between about 10 ns and about 500 ns. In other embodiments, the rise and fall time of the pulsed DC power or AC power may be between about 10 ns and about 100 ns. In some embodiments, the rise and fall time of the pulsed DC power or AC power may be about 500 ns. In some embodiments, the power supply **170** and/or the power supply **174** is an alternating current power supply. In other embodiments, the power supply **170** and/or the power supply **174** is a direct current power supply.

[0049] As shown, the electrode assembly **116** spans approximately the width of the substrate support assembly **138**. In other embodiments, the width of the electrode assembly **116** may be less than that of the substrate support assembly **138**. For example, the electrode assembly **116** may span between about 10% to about 80%, such as about 20% and about 40%, of the width of the substrate support assembly **138**. In embodiments where the width of the electrode assembly **116** is shorter than the width of the substrate support assembly **138**, the actuator **190** may scan the electrode assembly **116** across the surface of the substrate **140** positioned on the first surface **134** of the substrate support assembly **138**. For example, the actuator **190** may scan such that the electrode assembly **116** scans the entire surface of the substrate **140**. In other embodiments, the actuator **190** may scan only certain portions of the substrate **140**. Alternatively, the substrate support assembly **138** may scan underneath the electrode assembly **116**.

[0050] In some embodiments, one or more magnets **196** may be positioned in the processing chamber **100**. In the embodiment shown in FIG. **1**, the magnets **196** are coupled to the inside surface of the sidewalls **106**. In other embodiments, the magnets **196** may be positioned in other locations within the processing chamber **100** or outside the processing chamber **100**. For example, the magnets **196** may be positioned within the processing chamber **100** and adjacent to the bottom **108** and/or the lid assembly **110**. The magnets **196** may be, for example, permanent magnets or electromagnets. Representative permanent magnets include ceramic magnets and rare earth magnets.

[0051] In embodiments where the magnets **196** include electromagnets, the magnets **196** may be coupled to a power supply (not shown). The magnets **196** are configured to generate a magnetic field in a parallel direction, a perpendicular direction, or other direction relative to the electric field generated by electrode assembly **116** and/or the electrode assembly **118**. The magnets **196** may be configured to generate a field strength across the first surface **134** of the substrate support assembly **138** of between about 0.1 Tesla (T) and about 10 T, such as between about 1 T and about 5 T. In embodiments including a magnetic field, the magnets **196** may remain stationary or move relative to the first surface **134** of the substrate support assembly **138**.

[0052] FIG. **2** illustrates a top view of one embodiment of the electrode assembly **116** of FIG. **1**. In the embodiment shown in FIG. **2**, the electrode assembly **116** includes at least a first electrode **258** and a second electrode **260**. The first electrode **258** includes a first terminal **210**, a support structure **230**, and one or more antennas **220**. The second electrode **260** includes a second terminal **211**, a support structure **230**, and one or more antennas **221**. The first terminal **210**, the support structure **230**, and the one or more antennas **220** of the first electrode **258** may form a unitary body. Alternatively, the first electrode **258** may include separate portions that may be coupled together. For example, the one or more antennas **220** may be detachable from the support structure **230**. The second electrode **260** may similarly be a unitary body or be comprised of separate detachable components. The first electrode **258** and the second electrode **260** may be prepared by any suitable methods. For example, the first electrode **258** and the second electrode **260** may be fabricated by machining, casting, or additive manufacturing.

[0053] In one embodiment, the support structure **230** may be made from a conductive material, a semiconductive material, or substantially non-conductive materials. For example, the support structure **230** may be made of one or more of silicon, polysilicon, silicon carbide, molybdenum, aluminum, copper, graphite, silver, platinum, gold, palladium, zinc, other materials compatible with processing conditions in the chamber **100**, or mixtures thereof. The support structure **230** may have any desired dimensions. For example, the length L_s of the support structure **230** may be between about 25 mm and about 450 mm, for example, between about 100 mm and about 300 mm. In some embodiments, the support structure **230** has a length L_s approximately equal to a diameter of a standard semiconductor substrate. In other embodiments, the support structure **230** has a length L_s that is larger or smaller than the diameter of a standard semiconductor substrate. For example, in different representative embodiments, the length L_s of the support structure **230** may be about 25 mm, about 51 mm, about 76 mm, about 100 mm, about 150 mm, about 200 mm, about 300 mm, or about 450 mm.

[0054] The width W_s of the support structure **230** may be between about 2 mm and about 25 mm. In other embodiments, the width W_s of the support structure **230** is less than about 2 mm or greater than about 25 mm. The thickness of the support structure **230** may be between about 1 mm and about 10 mm, such as between about 2 mm and about 8 mm, such as about 5 mm. In other embodiments the support structure may have a thickness of less than about 1 mm or greater than about 10 mm. In some embodiments, the support structure **230** may have a cross-section that is square, cylindrical, rectangular, oval, rods, or other shapes. Embodiments having round exterior surfaces may avoid arcing.

[0055] The support structure **231** may be made of the same materials as the support structure **230**. Alternatively, the support structure **230** and the support structure **231** may be made of different materials. The lengths L_s, widths W_s, and thicknesses of the support structure **230** and the support structure **231** may be the same or different. The one or more antennas **220** of the first electrode **258** may also be made

from a conductive material. The one or more antennas **220** may be made from the same materials as the support structure **230**. Each of the antennas **220** may have the same dimensions. Alternatively, some of the one or more antennas **220** may have different dimensions than one or more of the other antennas **220**. The antennas **221** may be made of the same range of materials as the antennas **220**. The range of dimensions suitable for the antennas **220** is also suitable for the antennas **221**.

[0056] The number of the antennas **220** may be between about 1 and about 40 antennas. For example, the number of the antennas **220** may include between about 4 and about 40, such as between about 10 and about 20. Each of the antennas **220** may be substantially parallel to each of the other antennas **220**. Each of the antennas **221** may be similarly positioned with respect to the support structure **231** and each other antenna **221**. In one example, the support structure **230** and the support structure **231** are straight. In other example, the support structure **230** and the support structure **231** may not be straight, such as curved, jagged, or have other profiles or shapes. In these embodiments, each of the antennas **220** may still be substantially parallel to each of the other antennas **220**.

[0057] Each of the antennas **220** has a terminal end **223** and a terminal end **225**. A distance C is defined between the support structure **230** and the terminal end **225**. A distance C' is defined between the support structure **231** and the terminal end **223**. Each of the distances C and C' may be between about 1 mm and about 10 mm. A distance A is defined between facing surfaces of one of the antennas **221** and an adjacent one of the antennas **221**. The distance A' is defined between facing surfaces of one antenna **220** and an adjacent one the antennas **220**. The distances A and A' may be greater than about 6 mm. A distance B is defined between facing surfaces of one of the antennas **220** and an adjacent one of the antennas **221**. The distance B may be, for example, greater than about 1 mm. The strength of an electric field generated between an antenna **220** and an adjacent antenna correlates with the distance B. For example, a smaller distance B correlates with a stronger electric field. Accordingly, in embodiments where a stronger electric field is desired, a smaller distance B may be advantageous.

[0058] In operation, the power supply **170** may supply a voltage to the first terminal **210** and/or a power supply **170'** may provide a voltage to the second terminal **211**. The power supply **170'** may be substantially similar to the power supply **170**. The supplied voltage creates an electric field between each antenna of the one or more antennas **220** and each antenna of the one or more antennas **221**. The electric field will be strongest between an antenna of the one or more antennas **220** and an adjacent antenna of the one or more antennas **221**. The interleaved and aligned spatial relationship of the antennas **220**, **221** produces an electric field in a direction parallel to the plane defined by the first surface **134** of the substrate support assembly **138**.

[0059] The substrate **140** is positioned on the first surface **134** of the substrate support assembly **138** such that the latent image lines **155** are parallel to the electric field lines generated by the electrode assembly **116**. Since the charged species **255** are charged, the charged species **255** are affected by the electric field. The electric field drives the charged species **255** generated by the photoacid generators in the photoresist layer **150** in the direction of the electric field. By driving the charged species **255** in a direction parallel with the latent image lines **155**, line edge roughness may be reduced. The uniform directional movement is shown by the double headed arrow **270**. In contrast, when a voltage is not applied to the first terminal **210** or the second terminal **211**, an electric field is not created to drive the charged species **255** in any particular direction. As a result, the charged species **255** may move randomly, as shown by the arrows **270'**. In other embodiments, the substrate **140** may be oriented differently relative to the antennas **220**, **221**. For example, the antennas **220**, **221** may be parallel to the latent image lines **155**.

[0060] FIG. **3** illustrates a schematic, side cross-sectional view of the substrate support assembly **138** of FIG. **1** having the electrode assembly **118** embedded therein. The electrode assembly **118** is embedded between the first surface **134** and the second surface **126** of the body **124** of the substrate support assembly **138**. The electrode assembly **118** has a first surface **334** and a second surface **326**. The first surface **334** and the second surface **326** are opposite each other and substantially parallel to the first surface **134** of the substrate support assembly. The first surface **334** of the electrode assembly **118** is closer than the second surface **326** to the first surface **134** of the substrate support assembly **138**. The distance D represents the distance separating the first surface **134** of the substrate support assembly **138** from the first surface **334** of the electrode assembly. The distance D may be between about 0.1 mm and about 100 mm. For example, the distance D may be between about 8 mm and about 14 mm. The distance D may be selected to control the strength of the electric field provided by the electrode assembly **118** to the first surface **134** and/or the photoresist layer **150**. The strength of the electric field generally influences and controls the rate of diffusion of the charged species **255**.

[0061] The substrate support assembly **138** has outer side surfaces **348** and the electrode assembly **118** has outer side surfaces **328**. The distance E represents a rim between the outer side surfaces **328** and the outer side surfaces **348**. The distance E may be, for example, any distance suitable for the distance D. The distance E may be constant around the electrode assembly **118**, or the distance E may vary. The thickness of the electrode assembly **118** is represented by the distance T_A. The distance T_A may be any suitable thickness for the antennas **220**, **221** discussed above. As shown, the electrode assembly **118** is coupled to the power supply **174**. The properties of the power supplied by the power supply **174** to the electrode assembly **118** may be as described above in relation to the power supply **170** of FIG. **1**.

[0062] FIG. **4**A depicts one example of the substrate support assembly **138** with an intermediate medium **402** disposed in the processing volume **112** and retained by the confinement ring **154** above the substrate **140**. Without the intermediate medium **402** positioned in the processing volume **112**, an air gap is typically defined in the processing volume **112** between the substrate **140** and the electrode assembly **116**. The dimension of the air gap defined in the processing volume **112** may be determined by the distance where the electrode assembly **116** is positioned approximate to the substrate **140**. For example, when the electrode assembly **116** is positioned close to the photoresist layer **150** disposed on the substrate **140**, a smaller dimension of the air gap may be defined in the processing volume **112**. In contrast, when the electrode assembly **116** is positioned

relatively far and distanced away from the substrate **140**, a larger dimension of the air gap may be defined in the processing volume **112**.

[0063] It is believed that air medium (i.e., air gap) formed in the processing volume **112** may adversely result in a voltage drop when a voltage power is applied to the electrode assemblies **116**, **118**. As the dielectric constant in the substrate **140** and in the air are very different, e.g., approximately 11.7 for the substrate **140** and 1 for air, when the voltage supplied to the electrode assembly **116** to generate an electric field to the substrate **140**, a significant voltage drop is often observed when voltage is transmitting through the air gap formed in the processing volume **112** prior to reaching to the photoresist layer **150** disposed on the substrate **140**. It is believed the low dielectric constant in air, e.g., dielectric constant of 1, significantly changes the voltage level applied from the electrode assembly **116**. Thus, by inserting a material with relatively high dielectric constant, such as greater than about 10, to replace the air gap defined in the processing volume **112**, the voltage applied to form the electric field therein may be maintained at a desired level without significant loss until reaching to the photoresist layer **150** disposed on the substrate **140**.

[0064] In one example, intermediate medium **402** placed in the processing volume may be liquid solution, such as DI water, organic gel, organic solution, inorganic solution, or other suitable medium that has a suitable dielectric constant configured to maintain the voltage level transmitting therethrough without significant voltage drop. In one example, DI water, e.g., a material having a dielectric constant about 80, is disposed and placed in the processing volume **112** above the substrate support assembly **138** confined by the confinement ring **154**. In other embodiments, the intermediate medium **402** may be a material which is compatible (i.e. does not solvate the photoresist layer **150**, or solvates the photoresist layer **150** at a rate which does not significantly affect patterning) with the photoresist layer **150**. As previously mentioned, the intermediate medium **402** has a dielectric constant which prevents or reduces a voltage drop between the electrode assemblies **116**, **118**.

[0065] In one example, the intermediate medium **402** may be supplied from the intermediate medium source **172** through the intermediate medium dispensing tool **173** to substantially fill the processing volume **112**. The intermediate medium **402** disposed in the processing volume **112** may create an interface **404** in a close approximation to a downward surface **406** of the electrode assembly **116**. After the intermediate medium source **172** is filled in the processing volume **112**, the electrode assembly **116** may be lowered down to keep a minimum or negligible distance **407** between the electrode assembly **116** and the intermediate medium source **172**. As a result, the likelihood of voltage drop caused by the low dielectric constant air gap may be completely or substantially reduced.

[0066] Materials other than DI water may also be utilized as the intermediate medium source **172** to fill in the region of the processing volume **112** confined by the confinement ring **154**, as shown in FIG. **4**B. In the example depicted in FIG. **4**B, a gel or flowable organic droplets **410** with a dielectric constant greater than about 9 may also be used to fill the air gap disposed in the processing volume **112**. The gel or flowable organic droplets **410** may be spun-on to the substrate **140** until an interface **412** of the gel or flowable organic droplets **410** is defined in a close approximation to the downward surface **406** of the electrode assembly **116** with minimum and/or negligible room for an air gap. A quantity of the gel or flowable organic droplets **410** needed to fill the air gap defined above the substrate support assembly **138** and confined by the confinement ring **154** depends on the geometry of those components. It is noted that the gel or flowable organic droplets **410** may be continuously added until the processing volume **112** above the substrate is substantially full without leaving an undesired air gap touching the surface of the substrate **140**.

[0067] FIG. **5**A depicts another embodiment of the electrode assembly **116** with a confinement ring **502** disposed on an edge of the electrode assembly **116** from its downward surface **406**. Instead of liquid medium, a solid state medium **504** may be utilized to be positioned below and in contact with the downward surface **406** of the electrode assembly **116** within the area confined by the confinement ring **502**. After the solid state medium **504** is in place, the electrode assembly **116** may then be lowered down by the actuator **190** to have the solid state medium **504** in contact with the photoresist layer **150** disposed on the substrate **140**, as shown in FIG. **5**B. By carefully selecting the qualities and properties of the solid state medium **504**, e.g., with desired dielectric constant, the solid state medium **504** enables maintenance of a desired voltage for electric field generation between the electrode assemblies **116**, **118**.

[0068] In one example, the solid state medium **504** may be a solid disk having a size that may covers an entire surface of the photoresist layer **150** disposed on the substrate **140**. The solid state medium **504** may be attached to the electrode assembly **116** by any suitable techniques, including mechanical bonding or chemical bonding. The solid state medium **504**, when positioned above the photoresist layer **150**, may be placed in a position confined by the confinement ring **502** in close approximation to the photoresist layer **150** with minimum and/or negligible room for an air gap. It is noted that the phrase "negligible room" as described here may be a space less than 10 micrometers in height. In one example, the solid state medium **504** may be fabricated from a material with high a dielectric constant greater than about 10. Suitable examples of the solid state medium **504** include quartz or TiO_2, among others.

[0069] FIG. **6** illustrates a processing system **600** that may be used to process a substrate according to embodiments disclosed herein. As shown, the processing system **600** includes a load port **610**, a coating chamber **620**, a processing chamber **100**, an exposure chamber **630** (such as a scanner), a second processing chamber **100**, a development chamber **640**, and a post-processing chamber **650**. Each chamber of the processing system **600** is coupled to each adjacent chamber by a transfer chamber **605** or a transfer chamber **615**. The transfer chambers **605** and the transfer chamber **615** may be substantially similar or different.

[0070] The load port **610** may be used to introduce or remove substrates into or out of the processing system **600**. The coating chamber **620** may be used, for example, for applying a photoresist to a substrate. The coating chamber **620** may be, for example, a spin coater. The exposure chamber **630** may be used for exposing the substrate to electromagnetic energy in order to form a latent acid image in a photoresist layer on a substrate. The development chamber **640** may be used, for example, for removing portions of the photoresist layer. The post-processing chamber **650** may be used, for example, to perform a variety of

post-processing steps on a substrate. The processing chamber **100** may be used for a pre-exposure bake, a post-exposure bake, and/or other processing steps. As described above, the processing chamber **100** may include one or more electrode assemblies **118**, a remote plasma source **160**, and magnets **196**. However, it is to be understood that the coating chamber **620**, the exposure chamber **630**, and the development chamber **640** may also be similarly equipped.

[0071] FIG. **7** is a flow diagram of a method **700** for processing a substrate, such as the substrate **140**. The method **700** for processing the substrate **140** includes multiple operations. The operations can be performed in any order, for example, sequentially, simultaneously, or any other desired order (except where the context excludes that possibility). The method can also include one or more other operations which are carried out before any of the defined operations, between two of the defined operations, or after all the defined operations (except where the context excludes that possibility). Not all embodiments may include all the operations.

[0072] At operation **710**, a photoresist is applied to the substrate **140** to form a photoresist layer **150**. The photoresist layer **150** may be applied by, for example, by spin coating inside a spin coating apparatus, such as the coating chamber **620** included in the processing system **600**. In such an embodiment, the substrate **140** may enter the processing system **600** through the load port **610** and thereafter be transferred to the coating chamber **620** through a transfer chamber **605**.

[0073] The photoresist material comprising the photoresist layer **150** may include a solvent, a photoresist resin, and a photoacid generator. The photoresist resin may be any positive photoresist resin or any negative photoresist resin. Representative photoresist resins include acrylates, novolacs resins, poly(methylmethacrylates), and poly(olefin sulfones). Other photoresist resins may also be used.

[0074] Prior to the photoresist layer **150** being exposed to electromagnetic radiation, the photoacid generator generates charged species **255**, such as an acid cation and an anion. The photoacid generator may also generate polarized species. The photoacid generator sensitizes the resin to electromagnetic radiation. Representative photoacid generators include sulfonate compounds, such as, for example, sulfonated salts, sulfonated esters, and sulfonyloxy ketones. Other suitable photoacid generators include onium salts, such as aryl-diazonium salts, halonium salts, aromatic sulfonium salts and sulfoxonium salts or selenium salts. Other representative photoacid generators include nitrobenzyl esters, s-triazine derivatives, ionic iodonium sulfonates, perfluoroalkanesulfonates, aryl triflates and derivatives and analogs thereof, pyrogallol derivatives, and alkyl disulfones. Other photoacid generators may also be used.

[0075] At operation **720**, the substrate **140** is then heated by a pre-exposure baking process. During the pre-exposure baking process, the substrate is heated to partially evaporate the photoresist solvents. The pre-exposure bake at operation **720** and the photoresist application at operation **710** may occur in the same chamber or in different chambers. For example, both operations **710**, **720** may occur in a spin coater or the substrate **140** may be transferred to a different processing chamber between operations **710**, **720**. In an embodiment using the processing system **600**, the substrate **140** may be transferred from the coating chamber **620** to the processing chamber **100** through the transfer chamber **605**.

[0076] At operation **730**, the substrate **140** then transferred to the exposure chamber **630** to expose substrate **140** to electromagnetic radiation for a lithographic exposure process. The substrate **140** and portions of the photoresist layer **150** are exposed to electromagnetic radiation. During exposure, portions of the photoresist layer **150** are selectively exposed and portions of the photoresist layer **150** are selectively unexposed. Portions of the photoresist layer **150** exposed to electromagnetic radiation may have different chemical properties than the portions of the photoresist layer **150** not exposed to the electromagnetic radiation.

[0077] The charged species **255** generated by the photoacid generator generally result in a latent acid image in the resist resin. In some embodiments, a photomask or reticle may be positioned between the photoresist layer **150**, and the photoresist layer **150** may be exposed to electromagnetic radiation through the mask or reticle. The mask or reticle may be configured to transfer a pattern containing lines to the photoresist layer **150**. In other embodiments, a pattern containing lines may be transferred to the photoresist layer **150** using maskless lithography techniques. The transferred latent image lines **155** may have any desired length, width, and spacing between latent image lines **155**. For example, in some embodiments, the line widths and line spacing may be between about 10 nm and about 16 nm. In other embodiments, the line widths and spacing may be less than about 10 nm or greater than about 16 nm. In some embodiments, the length of the latent image line **155** is about 150% of the width of the latent image line **155**. In other embodiments, the length of the latent image line **155** is greater than about 200% of the width of the latent image line **155**, such as for example, greater than about 1000% of the width of the latent image line **155**.

[0078] The electromagnetic radiation generally has a wavelength suitable for exposing the photoresist layer **150**. For example, the electromagnetic radiation may have a wavelength in the extreme ultra violet (EUV) range, such as between about 10 nm and about 124 nm. In other embodiments, the electromagnetic radiation may be generated by an argon fluoride laser. In such an embodiment, the electromagnetic radiation may have a wavelength of about 193 nm. In some embodiments, the wavelength may be 248 nm. Other embodiments may use different wavelengths. In some embodiments, the electromagnetic radiation is from an electron beam or an ion beam.

[0079] After exposure, at operation **740**, the substrate **140** is heated in a post-exposure bake stage during a post-exposure baking process to change the film properties exposed under electromagnetic radiation at operation **740**. The substrate **140** may be transferred from the exposure chamber **630** to the processing chamber **100** through the transfer chamber **615** for the post-exposure baking process. The substrate **140** may be positioned on the first surface **134** of the substrate support assembly **138** during the post-exposure baking process. The power supply **174** may provide power to the embedded heater **132** to heat the substrate **140** during the post-exposure baking process. The embedded heater **132** may quickly heat the substrate **140** and the photoresist layer **150**. For example, the embedded heater **132** may raise the temperature of the photoresist layer **150** from ambient temperature to between about 70° C. and about 160° C., such as between about 90° C. and 140° C., in less than about 2 seconds.

[0080] During the post-exposure bake at operation **740**, photoacid generators in the photoresist layer **150** may continue to alter the chemical properties of the exposed portions of the photoresist layer **150**. In addition to the baking process, an electrical field may be generated to the photoresist layer **150**, as described at operation **701**, while performing the post-exposure baking process at operation **740**. While applying the electric field between the electrode assembly **116** and/or the electrode assembly **118**, the charged species **255** may be guided in a desired direction by at least one of an electric field, a magnetic field, and/or a plasma. The magnetic field may be generated by, for example, the magnets **196**. The plasma may be generated by, for example, the remote plasma source **160**. With the utilization of intermediate medium **402**, gel or flowable organic droplets **410** or the solid state medium **504** in the processing volume **112**, the likelihood of voltage drop/loss applying to the electrode assemblies **116**, **118** for electric field generation may be significantly reduced or eliminated. While generating the electric field to the photoresist layer **150**, the substrate **140** may or may not have a relative motion to the electrode assemblies **116**, **118** as needed to alter the electric field strength at different locations of the photoresist layer **150**.

[0081] As noted above, the charged species **255** may be guided in any operation or in any combination of operations. In some embodiments, the charged species **255** are guided in one direction relative to the latent image lines **155** in one operation and guided in another direction relative to the latent image lines **155** in another operation. For example, during the exposure operation **730**, the charged species **255** may be guided in a direction perpendicular to the first surface **134**, and during the post-exposure bake operation **740**, the charged species **255** may be guided in the direction of the latent image lines **155** or both in the direction of the latent image lines **155** and in a direction perpendicular to the first surface **134**. In another embodiment, the charged species may be guided in the direction of the latent image lines **155** or both in the direction of the latent image lines **155** and in a direction perpendicular to the first surface **134** during the exposure operation **730** and guided in a direction perpendicular to the first surface **134** during the post-exposure bake at operation **740**. In some embodiments, the charged species **255** may be guided in different directions within a single phase. For example, in an exposure operation or during a post-exposure bake operation, the charged species **255** may be guided in a direction perpendicular to the first surface **134** for a portion of the stage and guided in a direction perpendicular to the first surface **134** and in a direction along the direction of the latent image lines for a portion of the stage. Such a variation in guided direction may be achieved by toggling the magnetic field on and off while applying a vertical magnetic field.

[0082] Referring now to FIG. **9**, an acid regeneration mechanism **900** is schematically represented to illustrate advantageous embodiments of the method **700** described herein. As described above with regard to operation **730**, the substrate **140** may be exposed to ionize the photoresist and the photoacid generator (PAG) generates cations (c^+) and anions (a^-). The ionization of the photoresist layer **150** may also result in the formation of protons (i.e. H+). The anions and cations dissociated from the PAG are generally relatively large compounds and do not readily move through the photoresist layer matrix. However, the protons are generally relatively small molecules and may move more quickly (i.e. relative to the cations/anions) throughout the photoresist layer matrix. Generally, the mechanism of acid generation is believed to proceed by protonation of the anion. As a result, acid generation in the photoresist layer **150** is generally limited by the availability of anions within the matrix.

[0083] Because electromagnetic radiation is generally exposed to the photoresist layer **150** in a top-down process, regions of the photoresist layer **150** adjacent the substrate **140** may not have adequate amounts of dissociated PAG to facilitate deprotection of the photoresist layer **150**. In other words, a gradient of cations/anions may exist in the photoresist layer **150**. For example, a higher concentration of cations/anion is present near a surface of the resist being exposed when compared to a region of the resist adjacent the substrate **140**. By actively influencing anion movement within the photoresist layer **150**, deprotection via acid generation may be achieved more quickly and with improved selectivity.

[0084] Operation **701** may be utilized to apply a field **902** to the substrate **140** and photoresist layer **150**. In one embodiment, the field **902** may have a positive polarity configured to facilitate movement of anions within the photoresist layer matrix. For example, the field may be oriented "up" to drive negatively charged anions toward the substrate **140**. Accordingly, anions may be moved through the matrix towards the substrate **140** where additional protons exist. As a result, the cation/anion concentration gradient may be changed by application of the field. As noted above, due to the mobility of protons within the matrix, the protons may be present in greater concentrations where acid formation is not readily occurring (due to the lack of anion for acid generation). As the acid is generated, byproducts of the resist solvation are generated by deprotecting the photoresist, in addition to protons which may be re-utilized to protonate anions. Accordingly, it is believed the acid regeneration mechanism **900** may be facilitated according to the embodiments described herein.

[0085] As a result of anions being moved through the matrix, acid may be generated more readily. Thus, deprotection in a desired pattern may be achieved in a more efficient and controlled manner. Similarly, sensitivity of the resist may also be improved by influencing the speed of acid regenerations and location where acid is regenerated. Moreover, line edge roughness and line width roughness may be reduced via anion movement and subsequent acid generation and regeneration.

[0086] In addition, contrast of the photoresist layer **150** may also be improved according to the embodiments described herein. The contrast of the photoresist may generally be defined as the development rate of the resist as a function of the absorbed light dose. In other words, the contrast of the photoresist is the ability of the resist to distinguish between "light" and "dark" regions. For example, the latent image lines **155** may be considered "light" regions because those regions were exposed to light during exposure in operation **130**. By improving the contrast, improved resolution may be achieved which results in an improved resist verticality profile. For example, footings may be reduced or eliminated and more precise patterning at advanced technology nodes may be realized utilizing the methods described herein.

[0087] Referring now to FIG. **8**, a graph **800** illustrating resist film thickness as a function of electromagnetic energy

dosage in post-exposure processes is provided. Data **802** is representative of a photoresist layer **150** upon which no immersion/no field is applied. Data **804** is representative of a photoresist layer **150** upon which an immersion lithography process was performed but no field was applied. Data **808** is representative of a photoresist layer **150** upon which immersion lithography was performed and a "downward" field was applied. Data **806** is representative of a photoresist layer **150** upon which immersion lithography was performed and an "upward" field was applied. Accordingly, it can be seen that data **806** with immersion/field-up provides adequate film thickness reduction as a greatly reduced exposure dosage when compared to conventional and other field guided/immersion processes. For example, the immersion/field-up process may reduce the exposure dosage by about 30% in certain embodiments.

[0088] By utilizing the embodiments described herein, the immersion/field-up process may enable lower dose utilization while maintaining adequate resist solvation. Accordingly, this may result in a greater contrast in the photoresist layer **150**. In one example, a 500% improvement in the contrast of the photoresist layer **150** was enabled utilizing the immersion/field-up process when compared to data **802** and **808**. As such, a steeper intensity transition (i.e. light/dark distinguishment) may be realized which may result in improved edge definition in the resist patter.

[0089] Subsequently, at operation **750**, a development process is performed to the areas exposed or not exposed to electromagnetic radiation from the substrate **140** to develop the photoresist layer **150**. In one embodiment, after operation **740**, the substrate **140** is transferred to a develop chamber, such as the develop chamber **640** depicted in FIG. **6**. In embodiments using the processing system **600**, the substrate **140** may be transferred from the processing chamber **100** to the development chamber **640** through the transfer chamber **605**. The development chamber **640** may also include the electrode assembly **116** coupled to one or more power supplies and/or the actuator **190** and magnets **196**. The substrate **140** may be positioned in the development chamber **640** relative to the electrode assembly **116** and magnets **196** as described in relation to the coating chamber **620**.

[0090] During operation **750**, the photoresist layer **150** may be developed by, for example, exposing the photoresist layer **150** to a developer, such as a sodium hydroxide solution, a tetramethylammonium hydroxide solution, xylene, or organic developers, such as alcohols or the like. The substrate **140** may be rinsed with, for example, water or n-butylacetate. After the development process at operation **750**, the latent image lines **155** may no longer be latent. The lines **155** on the substrate **140** will have less line edge/width roughness compared to conventional techniques. In addition, as a result of improved resist contrast, pattern verticality profiled may also be significantly improved.

[0091] Subsequently, at operation **760**, a post-treatment process may be performed on the substrate **140** to post-treat the substrate after the development process. The post-processing process may be performed, for example, in the post-processing chamber **650** depicted in FIG. **6**. In an embodiment using the processing system **600**, the substrate **140** may be transferred from the development chamber **640** through the transfer chamber **605** to the post-processing chamber **650** for post-processing. For example, after rinsing, the substrate **140** may be hard baked and inspected. After inspection, an etching process may be performed on the substrate **140**. The etching process uses the features of photoresist layer **150**, such as the lines **155**, to transfer a pattern to the layer **145**.

[0092] While performing the processes of applying the photoresist layer on the substrate at operation **710**, heating the substrate at operation **720**, exposing the substrate to electromagnetic radiation at operation **730**, heating the substrate at operation **740**, developing the substrate at operation **750**, and post-treating the substrate at operation **760**, a voltage may be applied to generate an electric field, as indicated at operation **701**, to guild the charged species **255** generated by the photoacid generator in a desired direction, such as a direction parallel to the x-y plane and in the direction of the latent image lines **155**, a direction parallel to the x-y plane and perpendicular to the latent image lines **155**, a different direction, or combinations thereof. With the intermediate medium **402**, the gel or flowable organic droplets **410** or the solid state medium **504** placed in between the electrode assembly **116** and the substrate **140** to avoid possible air gap defined therebetween, voltage applied thereto to generate the electric field may then be maintained at a desired level without undesired voltage drop or loss.

[0093] The previously described embodiments have many advantages, including the following. For example, the embodiments disclosed herein may reduce or eliminate voltage drop/loss while applying an electric field between an electrode assembly and a photoresist layer disposed on a substrate for line edge/width roughness reduction. In addition, resist sensitivity and contrast may be improved which may result in reduces line edge roughness and line width roughness.

[0094] While the foregoing is directed to embodiments of the present disclosure, other and further embodiments of the disclosure may be devised without departing from the basic scope thereof, and the scope thereof is determined by the claims that follow.

1. A photolithography method, comprising:

exposing a substrate having a photoresist layer disposed thereon to electromagnetic radiation, wherein the photoresist layer includes a photoacid generator;

ionizing the photoresist layer;

dissociating the photoacid generator to form anions and cations in a first resist region;

facilitating acid generation by protonating the anions in the first resist region;

applying an electromagnetic field to the substrate to move the anions within the photoresist layer to a second resist region; and

facilitating acid generation by protonating the anions in the second resist region.

2. The method of claim **1**, wherein the first region and the second region are different regions of the photoresist layer.

3. The method of claim **2**, wherein the first region is adjacent an exposed surface of the photoresist layer and the second resist region is adjacent the substrate.

4. The method of claim **1**, wherein the applying the electromagnetic field comprises:

generating a voltage potential between a first electrode assembly and a second electrode assembly, wherein the substrate is positioned between the first electrode assembly and the second electrode assembly.

5. The method of claim **4**, wherein a distance between the first electrode assembly and the second electrode assembly is between about 0.5 mm and about 10 mm.

6. The method of claim **1**, wherein the electromagnetic field is applied via a non-gas phase medium.

7. The method of claim **6**, wherein the electromagnetic field is an electric field with a voltage potential of between about 40 V and about 4000 V.

8. The method of claim **6**, wherein the non-gas phase medium is selected to be predominantly unreactive with the photoresist layer.

9. The method of claim **1**, wherein the electromagnetic field has a positive polarity.

10. The method of claim **9**, wherein the electromagnetic field is oriented in a direction configured to move the anions within the photoresist layer toward the substrate.

11. The method of claim **1**, wherein the electromagnetic radiation is extreme ultraviolet radiation.

12. The method of claim **1**, further comprising:

developing the photoresist layer; and

etching the substrate.

13. The method of claim **1**, wherein the protonating the anions in the first resist region, the applying an electromagnetic field to the substrate, and the protonating the anions in the second resist region are configured to improve sensitivity and contrast of the photoresist layer.

14. A photolithography method, comprising:

exposing a substrate having a photoresist layer disposed thereon to extreme ultraviolet radiation, wherein the photoresist layer includes a photoacid generator;

ionizing the photoresist layer;

dissociating the photoacid generator to form anions and cations in a first resist region adjacent an exposed surface of the photoresist layer;

heating the substrate and the photoresist layer;

facilitating acid generation by protonating the anions in the first resist region;

applying an electromagnetic field to the substrate via a non-gas phase medium to move the anions within the photoresist layer to a second resist region different than the first resist region; and

facilitating acid generation by protonating the anions in the second resist region.

15. The method of claim **14**, wherein the second resist region is adjacent the substrate.

16. The method of claim **14**, wherein the electromagnetic field is an electric field with a voltage potential of between about 40 V and about 4000 V.

17. The method of claim **16**, wherein the electromagnetic field has a positive polarity.

18. The method of claim **17**, wherein the electromagnetic field is oriented in a direction configured to move the anions within the photoresist layer toward the second region.

19. The method of claim **14**, wherein the protonating the anions in the first resist region, the applying an electromagnetic field to the substrate, and the protonating the anions in the second resist region are configured to improve sensitivity and contrast of the photoresist layer.

20. A substrate processing method, comprising:

applying a photoresist to a substrate in a first processing chamber;

transferring the substrate via a first transfer chamber to a second processing chamber;

heating the substrate in the second processing chamber;

transferring the substrate via second transfer chamber to a third processing chamber;

exposing the substrate to extreme ultraviolet radiation in the third processing chamber;

transferring the substrate via a third transfer chamber to a fourth processing chamber, wherein the second processing chamber and the fourth processing chamber are configured similarly;

applying an electric field to the substrate via a non-gas phase medium to cause movement of anions within the photoresist in the fourth processing chamber;

transferring the substrate via a fourth transfer chamber to a fifth processing chamber; and

developing the photoresist on the substrate in the fifth processing chamber.

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