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(54) **APPARATUS FOR FIELD GUIDED ACID PROFILE CONTROL IN A PHOTORESIST LAYER**

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H01L 21/027	(2006.01)
H01L 21/687	(2006.01)
H01L 21/683	(2006.01)

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(58) **Field of Classification Search**

USPC 396/611

See application file for complete search history.

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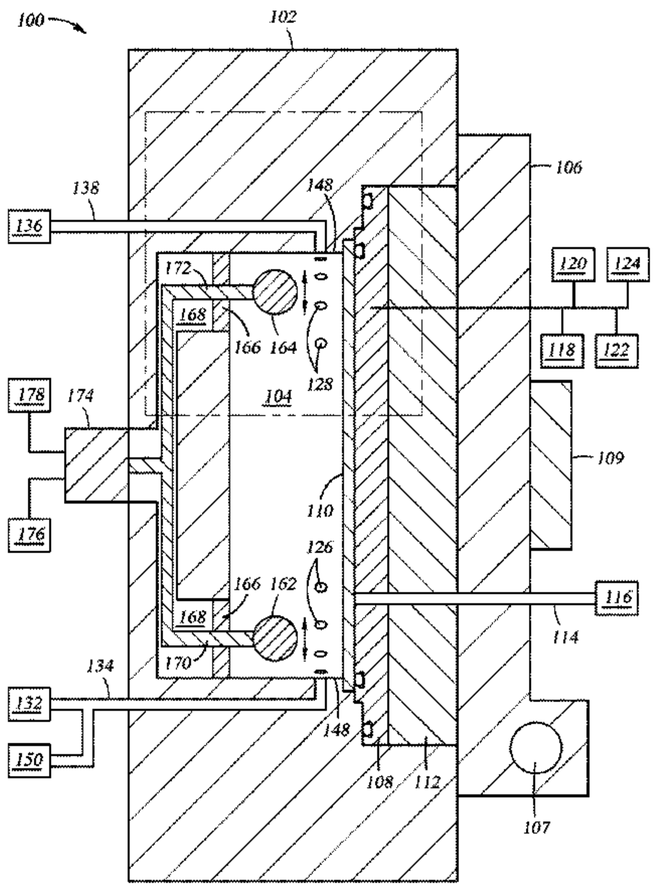
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(57) **ABSTRACT**

A process chamber having moveable electrodes for generating a parallel field within a process volume filled with a fluid is provided. In one implementation, a major axis of the process chamber is oriented vertically and a substrate support is disposed opposite a plurality of moveable electrodes extending along the major axis of the process chamber. In certain implementations, the substrate support is electrically floating and capable of rotating about a minor axis of the process chamber during processing of a substrate.

20 Claims, 5 Drawing Sheets



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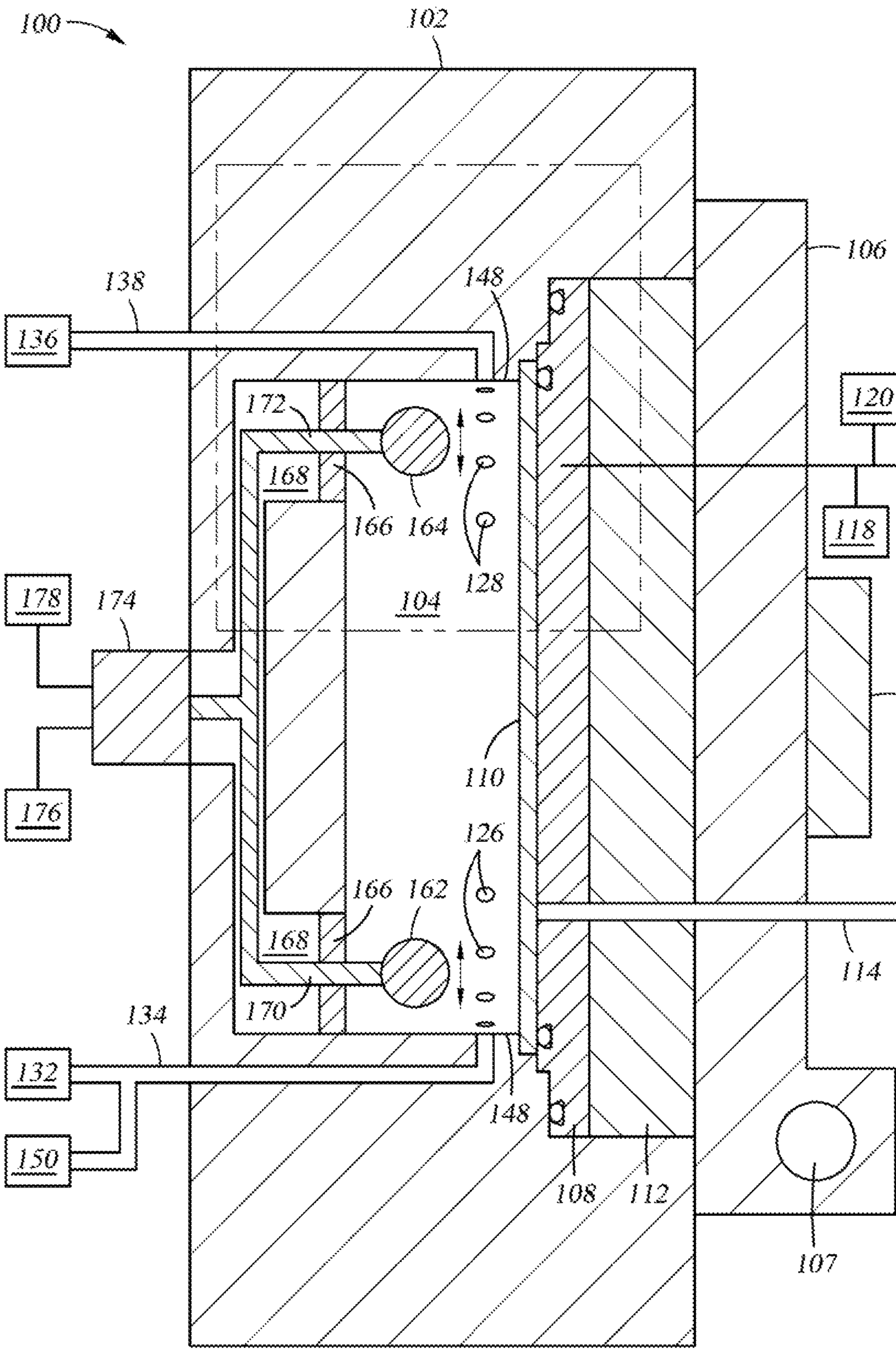

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Fig. 1

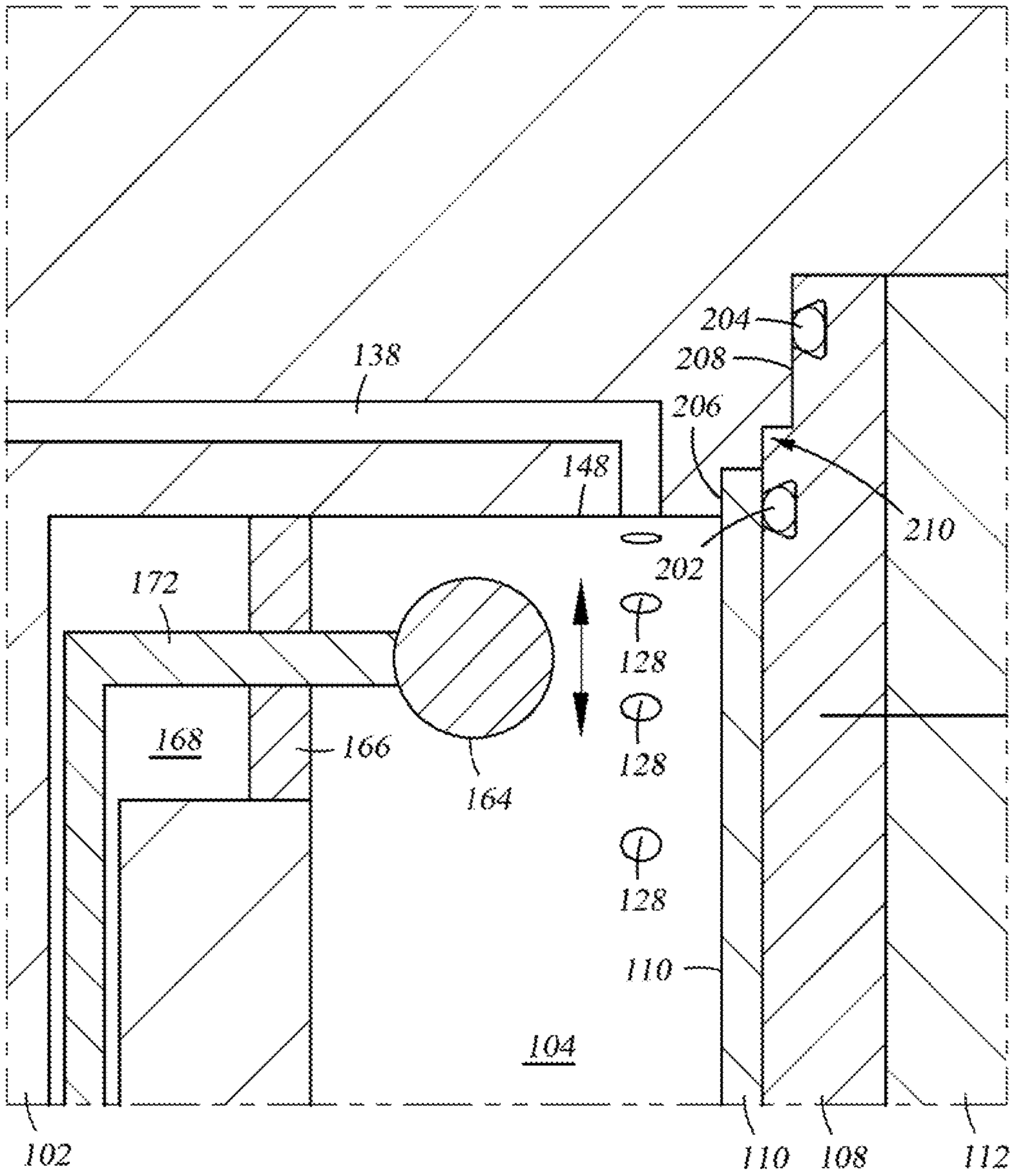

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Fig. 2

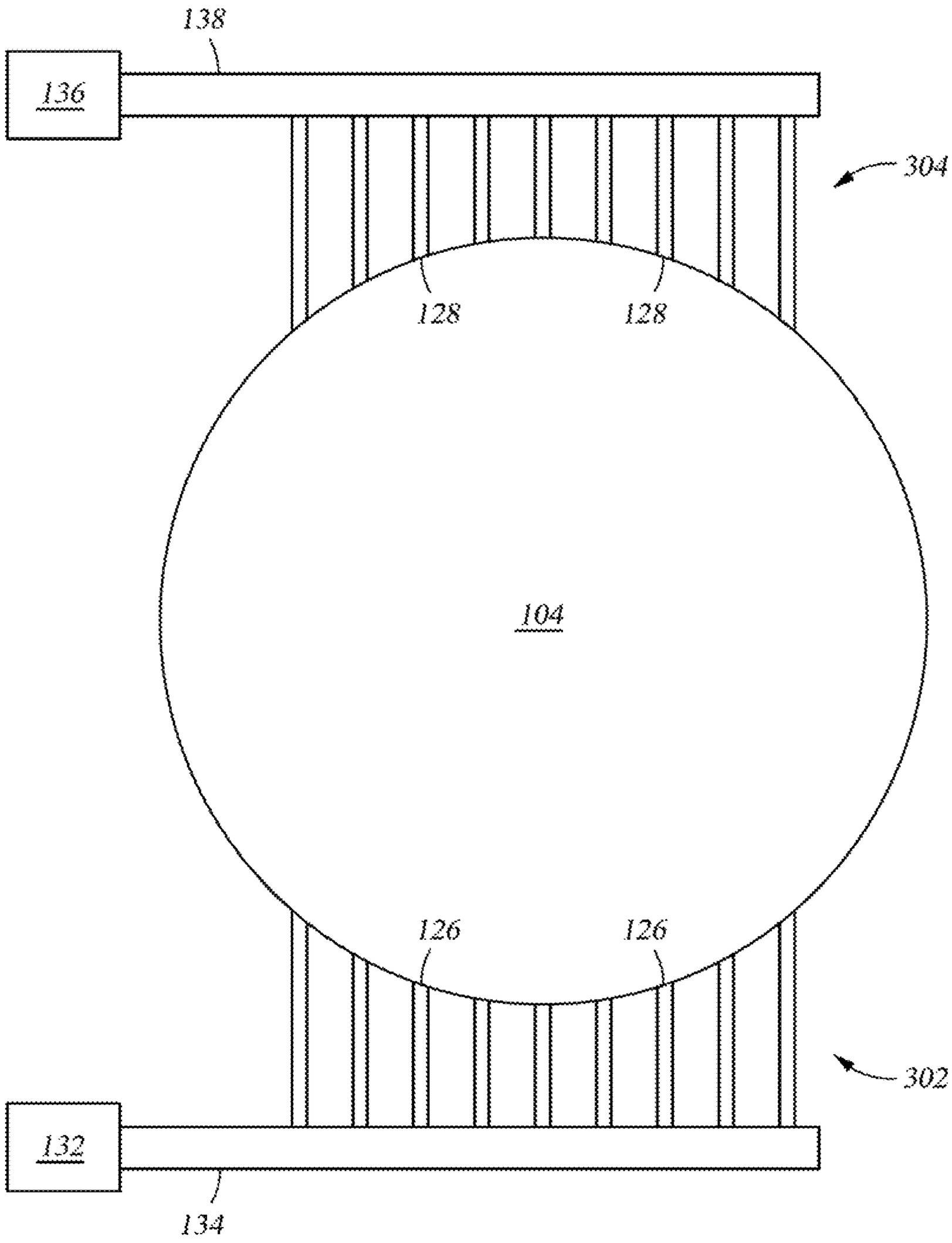


Fig. 3

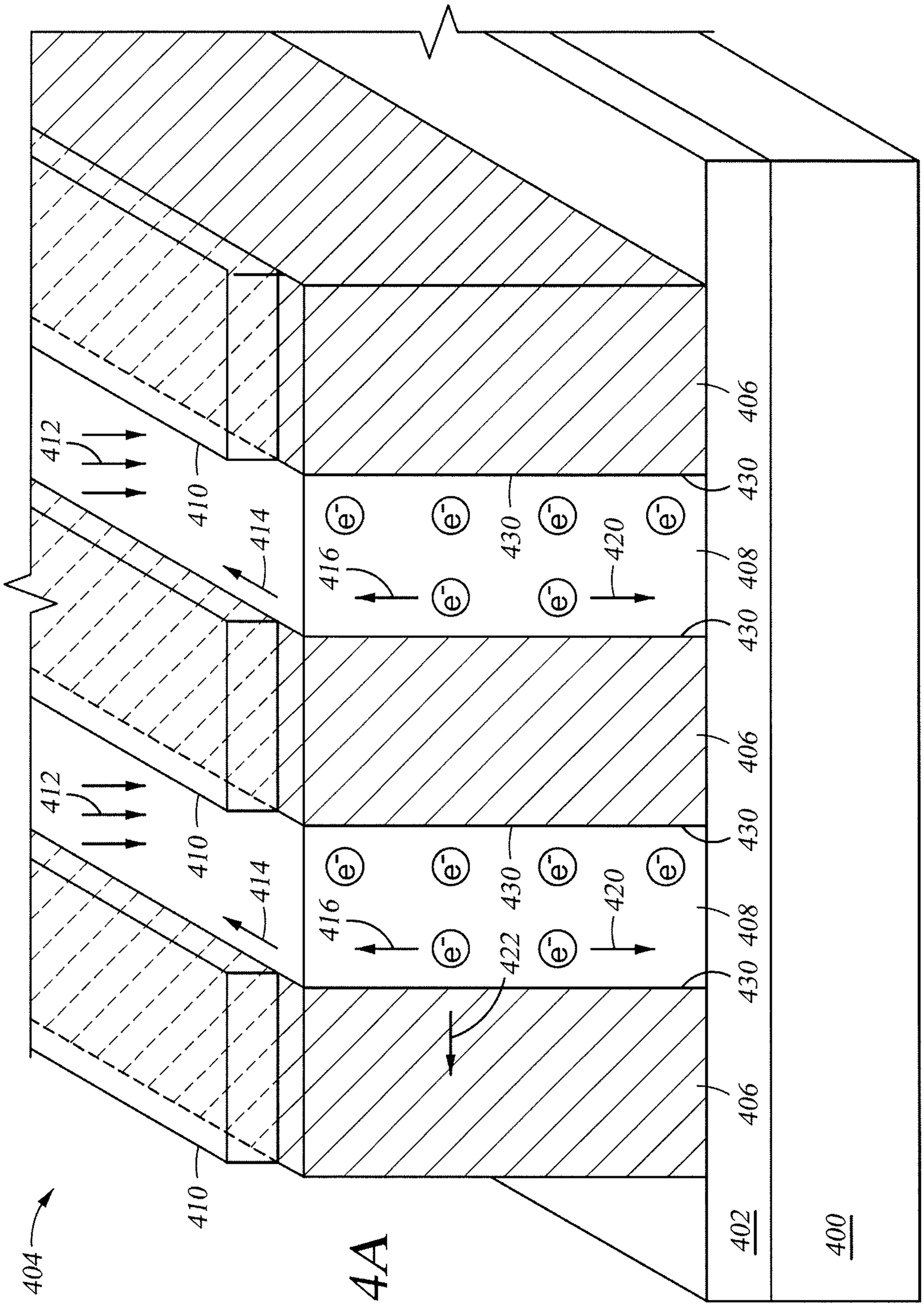


Fig. 4A

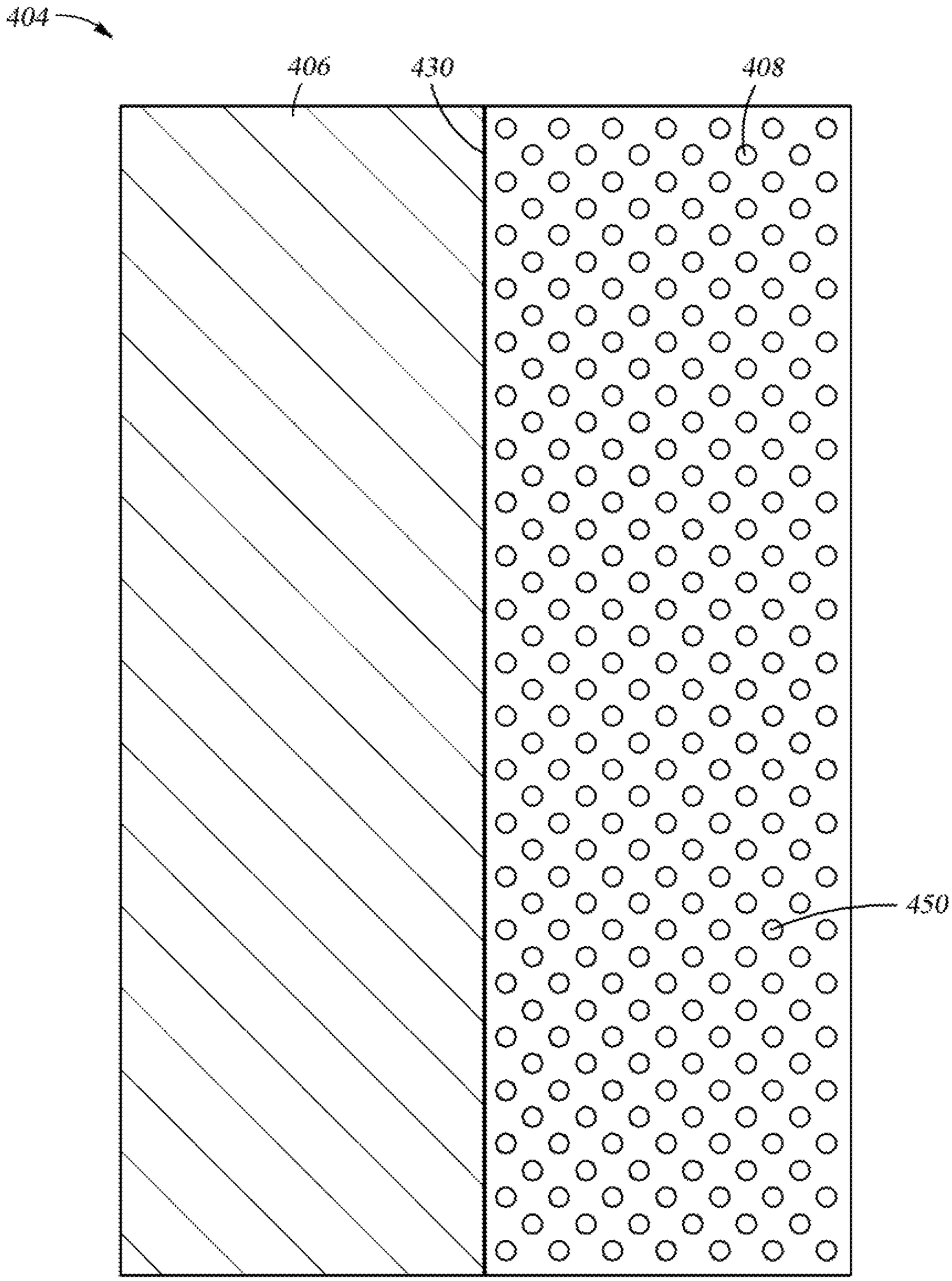


Fig. 4B

APPARATUS FOR FIELD GUIDED ACID PROFILE CONTROL IN A PHOTORESIST LAYER

CROSS-REFERENCE TO RELATED APPLICATIONS

This application claims benefit of U.S. Provisional Patent Application No. 62/440,016, filed Dec. 29, 2016, the entirety of which is herein incorporated by reference.

BACKGROUND

Field

Implementations of the present disclosure generally relate to apparatus for processing a substrate. More specifically, implementations described herein relate to apparatus processing a substrate with a photoresist layer disposed thereon.

Description of the Related Art

Integrated circuits have evolved into complex devices that can include millions of components (e.g., transistors, capacitors and resistors) on a single chip. Photolithography may be used to form components on a chip. Generally the process of photolithography involves several stages. Initially, a photoresist layer is formed on a substrate. The photoresist layer may be formed by, for example, spin-coating. 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, such as a wavelength in the extreme ultra violet region. The electromagnetic radiation may be from any suitable source, such as, for example, a 193 nm ArF laser, an electron beam, an ion beam, or other source. Excess solvent may then be removed in a pre-exposure bake process.

In an exposure stage, a photomask or reticle may be used to selectively expose certain regions of a photoresist layer disposed on the substrate to electromagnetic radiation. Other exposure methods may be maskless exposure methods. Exposure to light may decompose the photoacid generator, which generates acid and results in a latent acid image (defined at least in part by "latent image lines") 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 in the photoresist layer, changing the solubility of the resist of the photoresist layer during the subsequent development process.

After the post-exposure bake, the substrate, and, particularly, the photoresist layer may be developed and rinsed. After development and rinsing, a patterned photoresist layer is then formed on the substrate in order to transfer the pattern to an underlying material layer exposed by openings in the patterned photoresist layer via various etching processes. However, inaccurate control or low resolution of the lithography exposure process may result in the photoresist layer having being formed with undesirable dimensions, such as unacceptable line width roughness (LWR). Furthermore, during the exposure process, acid generated from the photoacid generator may diffuse randomly, including into regions under the mask where such acid is not intended to be diffused. This unintended diffusion may create undesired

wiggling and/or an undesired roughness profile at the interface of the patterned photoresist layer with the openings. Line width roughness (LWR) and undesired profiles of the photoresist layer may result in inaccurate feature transfer to the underlying material layer which may lead to device failure and/or yield loss.

Therefore, there is a need for apparatus and methods to improve profile control in a photoresist layer.

SUMMARY

In one implementation, an apparatus for processing a substrate is provided. The apparatus includes a chamber body defining a process volume having sidewalls. A major axis of the process volume is oriented vertically and a minor axis of the process volume is oriented horizontally. A moveable door is coupled to the chamber body, a vacuum chuck is coupled to the door, and a sliding seal is coupled to sidewalls of the chamber body and at least partially defining a portion of the process volume. A plurality of moveable electrodes are disposed in the process volume opposite the vacuum chuck and a plurality of shafts extend from the plurality of electrodes. The shafts extend through the sliding seal and a motor is coupled to the plurality of shafts.

In another implementation, an apparatus for processing a substrate is provided. The apparatus includes a chamber body defining a process volume having sidewalls, a first plurality of fluid ports formed in the sidewalls of the chamber body, and a second plurality of fluid ports formed in the sidewalls of the chamber body opposite the first plurality of fluid ports. The apparatus also includes a movable door coupled to the chamber body, a vacuum chuck coupled to the door, a sliding seal coupled to the sidewalls of the chamber body and at least partially defining a portion of the process volume. In addition, the apparatus includes a plurality of movable electrodes disposed in the process volume opposite the vacuum chuck, a plurality of shafts extending from the plurality of electrodes and the shafts extend through the sliding seal, and a motor coupled to the plurality of shafts.

In yet another implementation, an apparatus for processing a substrate is provided. The apparatus includes a chamber body defining a process volume having sidewalls and a major axis of the process volume is oriented vertically and a minor axis of the process volume is oriented horizontally. The apparatus also includes a first plurality of fluid ports formed in the sidewalls of the chamber body and a second plurality of fluid ports formed in the sidewalls of the chamber body opposite the first plurality of fluid ports along the major axis of the process volume. Further, the apparatus includes a movable door coupled to the chamber body, a vacuum chuck having a heating element disposed therein coupled to the door, and a sliding vacuum seal coupled to the sidewalls of the chamber body and at least partially defining a portion of the process volume. In addition, the apparatus includes a plurality of movable electrodes disposed in the process volume opposite the vacuum chuck, a plurality of shafts extending from the plurality of electrodes, the shafts extending through the sliding seal into a cavity disposed opposite the process volume, and a motor coupled to the plurality of shafts.

BRIEF DESCRIPTION OF THE DRAWINGS

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 implementations, some of which are illustrated in the appended drawings. It is to be noted, however, that the appended drawings illustrate only exemplary implementations and are therefore not to be considered limiting of its scope, may admit to other equally effective implementations.

FIG. **1** illustrates a cross-sectional view of a process chamber according to implementations described herein.

FIG. **2** illustrates a detailed view of a portion of the process chamber of FIG. **1** according to implementations described herein.

FIG. **3** illustrates a schematic, side view of various components of the process chamber of FIG. **1** according to implementations described herein.

FIGS. **4**A-**4**B illustrate an acid distribution control of a photoresist layer during an exposure process according to implementations described herein.

To facilitate understanding, identical reference numerals have been used, where possible, to designate identical elements that are common to the figures. It is contemplated that elements and features of one implementation may be beneficially incorporated in other implementations without further recitation.

DETAILED DESCRIPTION

Implementations described herein relate to apparatus and methods for processing a substrate. More specifically, a process chamber having movable electrodes for generating a field parallel to a substrate within a process volume filled with a fluid is provided. In one implementation, a major axis of the process chamber is oriented vertically and a substrate support is disposed opposite a plurality of movable electrodes extending along the major axis of the process chamber. In certain implementations, the substrate support is electrically floating and capable of rotating about a minor axis of the process chamber during processing of a substrate.

FIG. **1** illustrates a schematic, cross-sectional view of a process chamber **100** according to implementations described herein. In one implementation, the process chamber **100** is configured for performing immersion field guided post exposure bake (iFGPEB) processes. The chamber **100** is positioned in a vertical orientation such that when a substrate is being processed, a major axis of the substrate is oriented vertically and a minor axis of the substrate is oriented horizontally. While the illustrated implementations concern the chamber **100** in a vertical orientation, it is contemplated that the chamber **100** may be advantageously implemented with a horizontal orientation. The chamber **100** includes a chamber body **102**, which is manufactured from a metallic material, such as aluminum, stainless steel, and alloys and combinations thereof. Alternatively, the chamber body **102** is manufactured from polymer materials, such as polytetrafluoroethylene (PTFE), or high temperature plastics, such as polyether ether ketone (PEEK).

The body **102** defines, at least partially, a process volume **104** therein. For example, a sidewall **148** of the body **102** defines a diameter of the process volume **104**. A major axis of the process volume **104** is oriented vertically and a minor axis of the process volume **104** is oriented horizontally. A first plurality of fluid ports **126** are formed in the chamber body **102** through the sidewall **148**. A second plurality of fluid ports **128** are also formed in the sidewall **148** of the chamber body **102** opposite the first plurality of fluid ports **126**. The first plurality of fluid ports **126** are in fluid communication with a process fluid source **132** via first conduit **134**. The second plurality of fluid ports **128** are in fluid communication with a fluid outlet **136** via a second conduit **138**. The process fluid source **132**, either alone or in combination with other apparatus, is configured to preheat process fluid to a temperature of between about 70° C. and about 130° C., such as about 110° C., prior to the fluid entering the process volume **104**.

In one implementation, a purge gas source **150** is also in fluid communication with the process volume **104** via the first fluid conduit **134** and the first plurality of fluid ports **126**. Gases provided by the purge gas source **150** may include nitrogen, argon, other inert gases and the like to purge the processing volume **104** during or after iFGPEB processing. In one implementation, purge gas from the purge gas source **150** is provided to the process volume **104** to remove process fluid from the process volume **104**. In another implementation, the purge gas may be utilized to dry a substrate after processing the substrate with process fluid. When desired, purge gases may be exhausted from the processing volume **104** via the fluid outlet **136**.

A door **106** is operably coupled to the chamber body **102**. In the illustrated implementation, the door **106** is oriented in a processing position such that the door **106** is disposed adjacent to and abuts the chamber body **102**. The door **106** is formed from materials similar to the materials selected for the chamber body **102**. Alternatively, the chamber body **102** may be formed from a first material, such as a polymeric material, and the door **106** may be formed from a second material different from the first material, such as a metallic material. A shaft **107** extends through the door **106** and provides an axis (i.e. the Z-axis) about which the door **106** rotates to open and close the door **106**.

The door **106** may be coupled to a track (not shown) and the door **106** is configured to translate along the track in the X-axis. A motor (not shown) may be coupled to the door **106** and/or the track to facilitate movement of the door **106** along the X-axis. Although the door **106** is illustrated in a closed processing position, opening and closing of the door **106** may be performed by moving the door **106** away from the chamber body **102** along the X-axis prior to rotating the door **106** about the Z-axis. For example, the door **106** may rotate about 90° from the illustrated processing position to a loading position such that positioning of a substrate **110** on a vacuum chuck **108** can be performed with a reduced probability of substrate breakage during loading.

A backing plate **112** is coupled to the door **106** and the vacuum chuck **108** is coupled to the backing plate **112**. The backing plate **112** is formed from materials similar to the door **106** or the chamber body **102**, depending on the desired implementation. The vacuum chuck **108** may be formed from a non-metallic material or other insulative material, such as a ceramic material or the like. In addition, the material utilized for the vacuum chuck **108** may be a non-oxidative material to substantially reduce or prevent the probability of substrate oxidation via reaction of the process fluid with the vacuum chuck **108**. The materials utilized for the vacuum chuck **108** provide for desirable current uniformity within the process volume **104**. More specifically, the materials utilized for the vacuum chuck are selected to have a negligible influence of the electric field generated within the chamber **100** during processing.

In one implementation, the vacuum chuck **108** is electrically floating. As a result, a substrate **110** disposed on the vacuum chuck **108** is electrically floating. Thus, the substrate **110** is not electrically coupled to any conductive elements of the processing chamber **100** or to a ground. More specifically, electrically floating the substrate **110** helps to shape an electric field into a configuration in which

the electric field lines remain substantially parallel to the top (and/or bottom) surface of the substrate **110**, which is generally parallel to a substrate supporting surface of the vacuum chuck **108**.

The vacuum chuck **108** is sized to accommodate attachment of the substrate **110** thereon. The vacuum chuck **108** is also sized to allow for positioning adjacent the chamber body **102** and the process volume **104**. In one implementation, the vacuum chuck **108** is fixed to the backing plate **112** and the door **106**. In another implementation, the vacuum chuck **108** is rotatably coupled to the backing plate **112** and the door **106**. In this implementation, a motor **109** is coupled to the door **106** and is configured to impart rotational movement on either the backing plate **112** or the vacuum chuck **108**.

A vacuum source **116** is in fluid communication with a substrate receiving surface of the vacuum chuck **108**. The vacuum source **116** is coupled to a conduit **114** which extends from the vacuum source **116** through the door **106**, the backing plate **112**, and the vacuum chuck **108**. Generally, the vacuum source **116** is configured to vacuum chuck the substrate **110** to the vacuum chuck **108**.

In one implementation, a heat source **118**, a temperature sensing apparatus **120**, an optional electric field influence device **122**, and an optional sensing apparatus **124** are coupled to the vacuum chuck **108**. The heat source **118** provides power to one or more heating elements, such as resistive heaters or ceramic heaters, disposed within the vacuum chuck **108**. It is also contemplated that the heat source **118** provides power to heating elements disposed within the backing plate **112**. The heat source **118** is generally configured to heat either the vacuum chuck **108** and/or or the backing plate **112** to facilitate preheating of the substrate **110** and/or fluid during iFGPEB processes. The heat source **118** may also be utilized to maintain a desired temperature of the substrate and/or process fluid during substrate processing in addition to or distinct from preheating the process fluid. In one implementation, the heat source **118** is configured to heat the vacuum chuck **108** to a temperature of between about 70° C. and about 130° C., such as about 110° C.

The temperature sensing apparatus **120**, such as a thermocouple or the like, is communicatively coupled to the heat source **118** to provide temperature feedback and facilitate heating of the vacuum chuck **108**. The optional electric field influence device **122** is configured to ensure the vacuum chuck **108** remains electrically floating during processing. The optional sensing apparatus **124**, such as a voltmeter or the like, is communicatively coupled to the optional electric field influence device **122** to provide electrical feedback.

A plurality of electrodes **162**, **164** are disposed within the process volume **104** opposite the vacuum chuck **108**. In one implementation, the electrodes **162**, **164** are metallic antennas or rods. In another implementation, the electrodes **162**, **164** are conductive silicon carbide or graphite and may reduce the probability of metal contamination within the process chamber **100**. The electrodes **162**, **164** may have any desirable shape, such as a circular cross-section, an oblong cross-section, or a polygonal cross-section. The electrodes **162**, **164** extend a length similar to or greater than a diameter of the substrate **110**. For example, for a 300 mm diameter substrate, the electrodes **162**, **164** may have a length similar to or greater than about 300 mm. A first electrode **162** is disposed adjacent the sidewall **148** which has the first conduit **134** coupled thereto. A second electrode **164** is disposed adjacent the sidewalls **148** which has the second conduit **138** coupled thereto.

While the electrodes **162**, **164** are illustrated as being disposed near the sidewall **148** with a spacing between the electrodes **162**, **164** proximate the diameter of the substrate **110**, it is contemplated that the process volume **104** may be sized such that the electrodes **162**, **164** are spaced apart greater than a diameter of the substrate **110**. In this example, the electrodes **162**, **164** are disposed beyond the diameter of the substrate **110**. Accordingly, the sidewall **148** of the process chamber **100** may have a greater diameter to enable positioning of the electrodes **162**, **164** beyond the diameter of the substrate **110**. Similarly, the vacuum chuck **108** and backing plate **112** may be suitable sized to enable mating of the vacuum chuck **108** to the body **102** when the process volume **104** has a diameter greater than a diameter of the substrate **110**.

The first electrode **162** is coupled to a first shaft **170** which extends through a seal **166**. Similarly, the second electrode **164** is coupled to a second shaft **172** which extends through the seal **166**. The seal **166** is coupled to the body **102** at the sidewall **148** and extends radially inward where the seal **166** couples to a portion of the body disposed between the seal **166**. The seal **166** faces and at least partially defines a portion of the process volume **104**. As such, the seal **166** is exposed to the conditions maintained within the process volume **104** during processing, including exposure to process fluid and electric fields.

In one implementation, the seal **166** is a sliding vacuum seal. For example, the seal **166** allows for linear movement of the first and second shafts **170**, **172** while preventing the passage of fluids from the process volume **104** to reach a cavity **168** located behind the seal **166**. It is also contemplated that the seal **166** may prevent particles from entering the process volume **104** from the cavity **168**. The seal **166** is formed from materials which are suitable for preventing passage of a fluid therethrough while allowing for movement of the shafts **170**, **172**. In certain implementations, the seal **166** is formed from one or a plurality of gaskets which are formed from an elastomeric material.

Similar to the seal **166**, the cavity **168** is disposed between the sidewall **148** and the portion of the body **102** disposed between the seal **166**. The cavity **168** is generally void of obstructions to enable movement of the shafts **170**, **172** therein. For example, a width of the cavity **168** is sized to accommodate a stroke length of the electrodes **162**, **164** when the electrodes **162**, **164** are moved linearly in the process volume **104** (as indicated by the vertical double arrows). The cavity **168** also extends behind the portion of the body **102** disposed between the seal **166** (e.g. opposite the process volume **104**) and is sized to enable movement of the electrodes **162**, **164** by providing space for a common shaft (where the first shaft **170** and second shaft **172** meet) to translate linearly.

The shafts **170**, **172** coupled (via the common shaft) to a motor **174** which is disposed outside of and is coupled to the body **102**. The motor **174**, which may be coupled to a power source (not shown) is configured to impart linear movement to the shafts **170**, **172** and ultimately move the electrodes **162**, **164** within the process volume **104**. The motor **174** may be a stepper or servo motor or the like. In one implementation, the motor **174** is configured to raster scan in a singular plane (e.g. back and forth linear movement, and in the illustrated implementation, repetitive up and down movement, which may be continuous or step wise, depending upon the desired implementation).

A first power source **176** is electrically coupled to the first electrode **162**. For example, a conductive wire or the like may extend from the first power source **176** through the first

shaft **170** to the first electrode **162**. A second power source **178** is electrically coupled to the second electrode **162**. Similar to the first power source **176**, a conductive wire or the like may extend from the second power source **178** through the second shaft **172** to the second electrode **164**. The first power source **176** is configured to provide electrical current to the first electrode **162** with a first polarity and the second power source **178** is configured to provide electrical current to the second electrode **164** with a second polarity opposite the first polarity. For example, the first electrode **162** may be "positive" while the second electrode **164** is "negative."

Together, the configuration of the electrodes **162**, **164** and the fact that the substrate **110** is electrically floating helps to generate a desired electric field configuration. More specifically, the electrodes **162**, **164** are configured to generate an electric field parallel to a minor axis of the substrate **110**. In other words, the electrodes **162**, **164** are configured to generate an electric field normal to the major axis of the substrate **110**. The electrical floating of the substrate **110** helps to cause the electric field to be substantially parallel along a substantially large portion of the substrate **110**.

The power sources **176**, **178** may have various characteristics in order to provide the electric field described above. For example, the power sources **176**, **178** may be configured to supply between about 500 V and about 100 kV to the electrodes **162**, **164**, to generate an electric field having a strength between about 50 V/mm and about 100 MV/m, for example, between about 100 V/mm and about 1 MV/mm, such as about 200 V/mm. In some implementations, either or both of the power sources **176**, **178** are direct current (DC) power supply or a pulsed DC power supply. In pulsed DC implementations, pulsed DC waves may be from a half-wave rectifier or a full-wave rectifier. The DC power may have a frequency of between about 10 Hz and 1 MHz. The duty cycle of the pulsed DC power may be from between about 5% and about 95%, such as between about 20% and about 60%. In some implementations, the duty cycle of the pulsed DC power may be between about 20% and about 40%. In other implementations, the duty cycle of the pulsed DC power may be about 60%. The rise and fall time of the pulsed DC power may be between about 1 ns and about 1000 ns, such as between about 10 ns and about 500 ns. In other implementations, the rise and fall time of the pulsed DC power may be between about 10 ns and about 100 ns. In some implementations, the rise and fall time of the pulsed DC power may be about 500 ns.

In some implementations, either or both of the power sources **176**, **178** provide an alternating current power supply. The waveform applied by such an alternating current power supply may be a sinusoidal waveform. The frequency of such a sinusoidal waveform may be from between 1 Hz to 1 KHz, although the frequency is not limited to those numbers. This AC waveform may be combined with a pulse, as well. In other implementations, either or both of the power sources **176**, **178** are a direct current power supply. In some implementations, either or both of the power sources **176**, **178** may use a DC offset. The DC offset may be, for example, between about 0% and about 75% of the applied voltage, such as between about 5% and about 60% of the applied voltage.

The position of the electrodes **162**, **164** relative to the substrate **110** is such that a desired field strength is maintained without using excessive power. It is also contemplated that a distance between an edge of the substrate and the electrodes **162**, **164** is on the order of several millimeters to minimize the vertical field contribution in generating a horizontal field. While only two electrodes (electrodes **162**, **164**) are shown, it is contemplated that additional electrodes may be advantageously implemented. For example, multiple additional pairs of electrodes may be utilized. In these implementations, the additional pairs of electrodes are powered such that one electrode of the pair is "positive" and the other electrode of the pair is "negative." The orientation of the electrodes disposed in the process volume **104** is such that adjacent electrodes have opposite polarities. In other words, each electrode in a sequence of electrodes has a polarity opposite an immediately adjacent electrode (e.g. +, −, +, −).

Moving the electrodes **162**, **164** while the electric field and heat is applied helps to cause charged species (acid) in a resist disposed on the substrate **110** to move in a desired direction, allowing the interfaces defined by a latent image to be smoother than if no electric field were applied. It is contemplated that the electrodes may be moved in a manner to avoid creating turbulence of the process fluid in order to prevent generation of bubbles with a different dielectric constant than the dielectric constant of the process fluid. Moreover, it is believed that movement of the electrodes **162**, **164** helps to average out non-uniformities in the electric field adjacent the electrodes **162**, **164**. As a result of the aforementioned electrode arrangement and movement, acid generated upon exposure of a resist disposed on the substrate **110** may be modulated during iFGPEB processing to improve patterning and resist de-protection characteristics.

FIG. **2** illustrates a detailed view of a portion of the process chamber **100** of FIG. **1** according to implementations described herein. In operation, the process volume **104** is filled with process fluid during iFGPEB processing. To reduce the probability of process fluid leakage out of the process volume, a plurality of O-rings are utilized to maintain the fluid containment integrity of the process volume. A first O-ring **202** is disposed in the vacuum chuck **108** on the substrate receiving surface of the vacuum chuck **108**. The first O-ring **202** may be positioned on the vacuum chuck **108** radially inward from an outer diameter of the substrate **110**.

In one example, the first O-ring **202** is positioned on the vacuum chuck **108** a distance between about 1 mm and about 10 mm radially inward from the outer diameter of the substrate **110**. The first O-ring is positioned to contact the backside of the substrate **110** when the substrate is chucked to the vacuum chuck **108**. A first surface **206** of the sidewall **148** is shaped and sized to contact an edge region of the substrate **110** when the substrate **110** is in the illustrated processing position.

In another example, the first surface **206** of the sidewall does not contact the edge region of the substrate **110** when the substrate **110** is disposed in the processing position. In this example, the sidewall **148**, which as least partially defines the process volume **104**, has a diameter greater than a diameter of the substrate **110**. This implementation provides for an increased area within the process volume **104** for the electrodes **162**, **164** to move and provides sufficient area from the electrodes **162**, **164** to move beyond a diameter of the substrate **110**. In this implementation, it is contemplated that the field influence may be more profound at or near regions adjacent a circumference of the substrate **110** to further improve patterning and resist de-protection characteristics.

In one implementation, the first O-ring **202** is disposed in the vacuum chuck **108** opposite the first surface **206** of the sidewall **148**. It is contemplated that the first O-ring **202** may prevent the leakage of process fluid from the process volume **104** to a region behind the substrate **110**, such as the

substrate supporting surface of the vacuum chuck **108**. Advantageously, vacuum chucking of the substrate **110** is maintained and process fluid is prevented from reaching the vacuum source **116**.

The vacuum chuck **108** has a ledge **210** disposed radially outward of the first O-ring. The ledge **210** is disposed radially outward from the position of the first O-ring **202**. A second O-ring **204** is coupled to the vacuum chuck **108** radially outward of the ledge **210**. A second surface **208** of the sidewall **148** is shaped and sized to contact the vacuum chuck **108** adjacent to and extending radially inward from the outer diameter of the vacuum chuck **108**. In one implementation, the second O-ring **204** is disposed in contact with the second surface **208** of the sidewall **148** when the substrate **110** is disposed in a processing position. It is contemplated that the second O-ring **204** may prevent the leakage of process fluid from the process volume **104** beyond the outer diameter of the vacuum chuck **108**.

Each of the O-rings **202**, **204** are formed from an elastomeric material, such as a polymer or the like. In one implementation, the O-rings **202**, **204** have a circular cross-section. In another implementation, the O-rings **202**, **204** have a non-circular cross-section, such as a triangular cross section or the like. It is also contemplated that each of the O-rings **202**, **204** are subjected to a compressive force suitable to prevent the passage of process fluid beyond the O-rings **202**, **204** and fluidly seal the process volume **104**.

FIG. **3** illustrates a schematic, side view of various components of the process chamber **100** of FIG. **1** according to implementations described herein. The process volume **104** is illustrated with the first plurality of fluid ports **126** and the second plurality of fluid ports **128** formed therein. A first plurality of channels **302** are coupled between the first plurality of fluid ports **126** and the first conduit **134**. A second plurality of channels **304** are coupled between the second plurality of fluid ports **128** and the second conduit **138**.

While 10 channels of the first plurality of channels **302** are illustrated, it is contemplated that between about 5 channels and about 30 channels may be implemented, for example, between about 9 channels and about 21 channels. Similarly, between about 5 channels and about 30 channels may be utilized for the second plurality of channels **304**, for example, between about 9 channels and about 21 channels. The number of channels **302**, **304** is selected to enable suitable fluid flow rates during filling of the process volume **104**. The channels **302**, **304** are also configured to maintain the rigidity of the process volume **104** when the vacuum chuck **108** and substrate **110** are positioned against the first surface **206** of the chamber body **102**. In one implementation, 9 first channels **302** and 9 second channels **304** are coupled to the process volume **104**. In another implementation, 21 first channels **302** and 21 second channels **304** are coupled to the first process volume **104**.

The first plurality of channels **302** and the second plurality of channels **304** are formed in the body **102** of the process chamber **100**. Each of the first and second plurality of channels **302**, **304** has a diameter at the first fluid ports **126** and second fluid ports **128**, respectively, of between about 3.0 mm and about 3.5 mm, such as about 3.2 mm. In another implementation, the diameter of each channel along the diameter of the process volume **104** is different. In one implementation, the channels of the first plurality of channels **302** are evenly spaced across the diameter of the process volume **104**. Similarly, the channels of the second plurality of channels **304** are evenly spaced across the diameter of the process volume **104**. It is also contemplated that the channels of the first and second plurality of channels **302**, **304** may also be unevenly spaced across the diameter of the process volume **104**.

The spacing of the channels of the first and second plurality of channels **302**, **304** is configured to reduce turbulence of the process fluid entering and exiting the process volume **104**. Because turbulence generates bubbles in the process fluid and bubbles act as insulators within the subsequently applied electric field, measures are taken to reduce the formation of bubbles. As described in detail below, flow rates of process fluid are modulated, in combination with the design of the first and second plurality of channels **302**, **304**, to reduce turbulence.

A flow path of process fluid originates from the process fluid source **132** and travels through the first conduit **134** into the first plurality of channels **302**. The fluid exits the first plurality of channels **302** via the first fluid ports **126** into the process volume **104**. Once the process volume **104** is filled with process fluid, the process fluid exits the process volume **104** via the second fluid ports **128** into the second plurality of channels **304**. The process fluid continues into the second conduit **138** and is ultimately removed from the process chamber **100** in the fluid outlet **136**.

In one operational implementation, a first flow rate utilized to fill the process volume **104** with process fluid prior to activation of an electric field is between about 5 L/min and about 10 L/min. Once the process volume **104** is filled with process fluid, the electric field is applied and a second flow rate of process fluid between about 0 L/min and about 5 L/min is utilized during iFGPEB processing. The process fluid fill and processing time is between about 30 seconds and about 90 seconds, such as about 60 seconds. In one implementation, process fluid continues to flow during iFGPEB processing. In this implementation, the volume of the process volume **104** is exchanged between about 1 time and about 10 times per substrate processed. In another implementation, the process fluid is predominantly static during processing. In this implementation, the volume of the process volume **104** is not exchanged during substrate processing of each substrate.

In another operational implementation, a first flow rate is utilized to initially fill the process volume **104**. The first flow rate is less than 5 L/min for an amount of time to fill the process volume **104** such that the first fluid ports **126** are submerged. A second flow rate of greater than 5 L/min is then utilized to fill the remainder of the process volume **104**. During application of electric field in iFGPEB processing, a third flow rate of less than 5 L/min is utilized. The flow rate modulation between the first and second flow rates is configured to reduce turbulence of the fluid within the process volume **104** and reduce or eliminate the formation of bubbles therein. However, if bubbles are formed, the buoyancy of the bubbles enables the bubbles to escape from the process volume **104** via the second fluid ports **128**, thereby minimizing the insulating effect of the bubbles on the electric field during iFGPEB processing. Accordingly, a more uniform electric field may be achieved to improve iFGPEB processing.

FIG. **4**A depicts a photoresist layer **404** disposed on a material layer **402** formed on a substrate **400** during a lithography exposure process. As discussed above, an electric field from the electrodes **162**, **164** is applied during a post exposure baking process. During the lithographic exposure process, radiation **412** is directed to a first region **408** of the photoresist layer **404** while with a second region **406** of the photoresist layer **404** protected by a photomask **410**. Photoacid, shown as e^- in FIG. **4**A, is generated in the

exposed first region **408** in the photoresist layer **404** when photoacid generator (PAG) is exposed to the radiation **412**, such as a ultraviolet (UV) radiation. Although FIG. **4**A illustrates the photoacid with an "e^-" symbol, this is not specifically reflective of the actual charge of photoacid compounds, but of the fact that photoacid compounds generally are electrically charged.

In a conventional process, photoacid is primarily generated in the exposed first region **408** of the photoresist layer **404** during the light exposure process. During the post-exposure bake period, movement of photoacid is generally random and the interface between areas within the photoresist layer **404** that include the generated photoacid and areas that do not include the generated photoacid may comprise an unclear boundary (i.e., interface **430**). For example, the random movement may result in at least a portion of the photoacid diffusing into the second region **406**, as shown in the arrow **422**. Such photoacid drift may result in line edge roughness, resolution loss, photoresist footing, and profile deformation, which may cause inaccurate transfer of features to the underlying material layer **402**. This inaccurate transfer of features could lead to device failure.

By applying the electric field described above to the photoresist layer **404** during the post-exposure bake process, distribution of photoacid in the exposed first region **408** may be efficiently controlled and confined. The electric field as applied to the photoresist layer **404** may move photoacid in vertical directions (e.g., the y-direction shown by arrows **416** and **420**, which is substantially perpendicular to the planar surface of the substrate **400**) with minimal lateral motion (e.g., x direction shown by the arrow **422**). That is, the photoacid generally does not diffuse into the adjacent second region **406**. Generally, photoacid has a certain polarity that may be affected by an electric field applied thereto. Such an applied electric field will orient photoacid molecules in directions that are in accordance with the electric field. When such electric field is applied, the photoacid moves in a desired direction such that the photoacid generally does not cross into the second region **406**.

In another implementation, the substrate **110** may also be oriented with latent image lines relative to the electrodes **162**, **164** such that photoacid is moved in a horizontal directions (e.g. the z-direction **414**) to improve line edge roughness. Thus, it is contemplated that the orientation of the substrate **110** and the electrodes **162**, **164** may be utilized in various combinations to provide for improved patterning and resist de-protection characteristics.

FIG. **4**B depicts a top view of the photoresist layer **404** including a portion of the first region **408** and the second region **406** delineated by the interface **430**. After the electric and/or magnetic field is applied to the photoresist layer **404**, distribution of photoacid **450** is generally constrained to the first region **408** without diffusing cross to the second region **406**. Thus, by applying the electric field and/or magnetic field as described above, a clearly defined interface **430** may be obtained, thus forming a patterned photoresist layer with a sharp profile, a high resolution and reduced line edge roughness and defects.

In summation, apparatus and methods for improving iFGPEB processing are provided. The process chamber described herein enables efficient use of process fluid and improved application of electric field during iFGPEB operations. The movable electrodes and other aspects of the process chamber provide for improved field distribution and uniformity, thereby enabling improved photoresist development with improved resolution and reduced line roughness profiles. Thus, iFGPEB processing operations can be improved by utilizing the apparatus and methods described herein.

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

What is claimed is:

1. An apparatus for processing a substrate, comprising:
a chamber body defining a process volume having sidewalls, wherein a major axis of the process volume is oriented vertically and a minor axis of the process volume is oriented horizontally;
a moveable door coupled to the chamber body;
a vacuum chuck coupled to the door;
a sliding seal coupled to sidewalls of the chamber body and at least partially defining a portion of the process volume;
a plurality of moveable electrodes disposed in the process volume opposite the vacuum chuck, the plurality of moveable electrodes adapted to generate an electric field parallel to the major axis of the process volume;
a plurality of shafts extending from the plurality of electrodes, the shafts extending through the sliding seal; and
a motor coupled to the plurality of shafts.

2. The apparatus of claim **1**, further comprising:
a backing plate disposed between the vacuum chuck and the door.

3. The apparatus of claim **1**, wherein the moveable electrodes are made from one or more metallic materials.

4. The apparatus of claim **1**, wherein the moveable electrodes are made from a silicon carbide material.

5. The apparatus of claim **1**, wherein the moveable electrodes are made from a graphite containing material.

6. The apparatus of claim **1**, wherein the moveable electrodes are shaped as rods and have a circular cross-section.

7. The apparatus of claim **1**, further comprising:
a first plurality of fluid ports formed in the sidewalls of the chamber body, wherein the first plurality of fluid ports are in fluid communication with a first conduit.

8. The apparatus of claim **7**, further comprising:
a second plurality of fluid ports formed in the sidewalls of the chamber body, wherein the second plurality of fluid ports are in fluid communication with a fluid outlet via a second conduit.

9. The apparatus of claim **8**, wherein the second plurality of fluid ports are disposed opposite the first plurality of fluid ports along the major axis of the process volume.

10. The apparatus of claim **1**, wherein the sliding seal is a sliding vacuum seal.

11. The apparatus of claim **1**, wherein the sliding vacuum seal comprises a plurality of elastomeric gaskets.

12. The apparatus of claim **1**, wherein the motor coupled to the plurality of shafts is operable to move the electrodes parallel to the major axis of the process volume.

13. The apparatus of claim **1**, further comprising:
a rotational motor coupled to the vacuum chuck.

14. The apparatus of claim **1**, further comprising:
a rotational motor coupled to the backing plate.

15. The apparatus of claim **1**, further comprising:
heating elements disposed in the vacuum chuck.

16. The apparatus of claim **1**, wherein at least a portion of the plurality of shafts are disposed in a cavity disposed

opposite the process volume, wherein the cavity is defined by the sidewalls and the chamber body.

17. An apparatus for processing a substrate, comprising a chamber body defining a process volume having sidewalls;

a first plurality of fluid ports formed in the sidewalls of the chamber body;

a second plurality of fluid ports formed in the sidewalls of the chamber body opposite the first plurality of fluid ports;

a moveable door coupled to the chamber body;

a vacuum chuck coupled to the door;

a sliding seal coupled to sidewalls of the chamber body and at least partially defining a portion of the process volume;

a plurality of moveable electrodes disposed in the process volume opposite the vacuum chuck;

a plurality of shafts extending from the plurality of electrodes, the shafts extending through the sliding seal; and

a motor coupled to the plurality of shafts.

18. The apparatus of claim **17**, wherein the sliding seals is disposed between the process volume and a cavity disposed opposite the process volume.

19. An apparatus for processing a substrate, comprising

a chamber body defining a process volume having sidewalls, wherein a major axis of the process volume is oriented vertically and a minor axis of the process volume is oriented horizontally;

a first plurality of fluid ports formed in the sidewalls of the chamber body;

a second plurality of fluid ports formed in the sidewalls of the chamber body opposite the first plurality of fluid ports along the major axis of the process volume;

a moveable door coupled to the chamber body;

a vacuum chuck having a heating element disposed therein coupled to the door;

a sliding vacuum seal coupled to sidewalls of the chamber body and at least partially defining a portion of the process volume;

a plurality of moveable electrodes disposed in the process volume opposite the vacuum chuck;

a plurality of shafts extending from the plurality of electrodes, the shafts extending through the sliding seal into a cavity disposed opposite the process volume; and

a motor coupled to the plurality of shafts.

20. The apparatus of claim **19**, wherein the plurality of shafts connect at a common shaft, and wherein the common shaft is coupled to the motor.

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