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(54) **CONTROLLING PHOTO ACID DIFFUSION IN LITHOGRAPHY PROCESSES**

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G03F 7/20	(2006.01)
G03F 7/38	(2006.01)
G03F 7/004	(2006.01)
G03F 7/26	(2006.01)

(52) **U.S. Cl.**
CPC ***G03F 7/38*** (2013.01); ***G03F 7/0045*** (2013.01); ***G03F 7/26*** (2013.01)

(58) **Field of Classification Search**
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USPC 430/328, 330
See application file for complete search history.

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(57) **ABSTRACT**

Methods and apparatuses for minimizing line edge/width roughness in lines formed by photolithography are provided. The random diffusion of acid generated by a photoacid generator during a lithography process contributes to line edge/width roughness. Methods disclosed herein apply an electric field, a magnetic field, and/or a standing wave during photolithography processes. The field and/or standing wave application controls the diffusion of the acids generated by the photoacid generator along the line and spacing direction, preventing the line edge/width roughness that results from random diffusion. Apparatuses for carrying out the aforementioned methods are also disclosed herein.

12 Claims, 8 Drawing Sheets

POWER SUPPLY 175
SUPPLY SOURCES 104
POWER SUPPLY 170
ACTUATOR
POWER SOURCE 274
TO VACUUM PUMP
100 102 106 108 110 112 114 116 124 126 132 134 138 140 142 145 146 150 155 158 160 180 190 196
d
Z Y X

FIG. 1

FIG. 2

FIG. 3

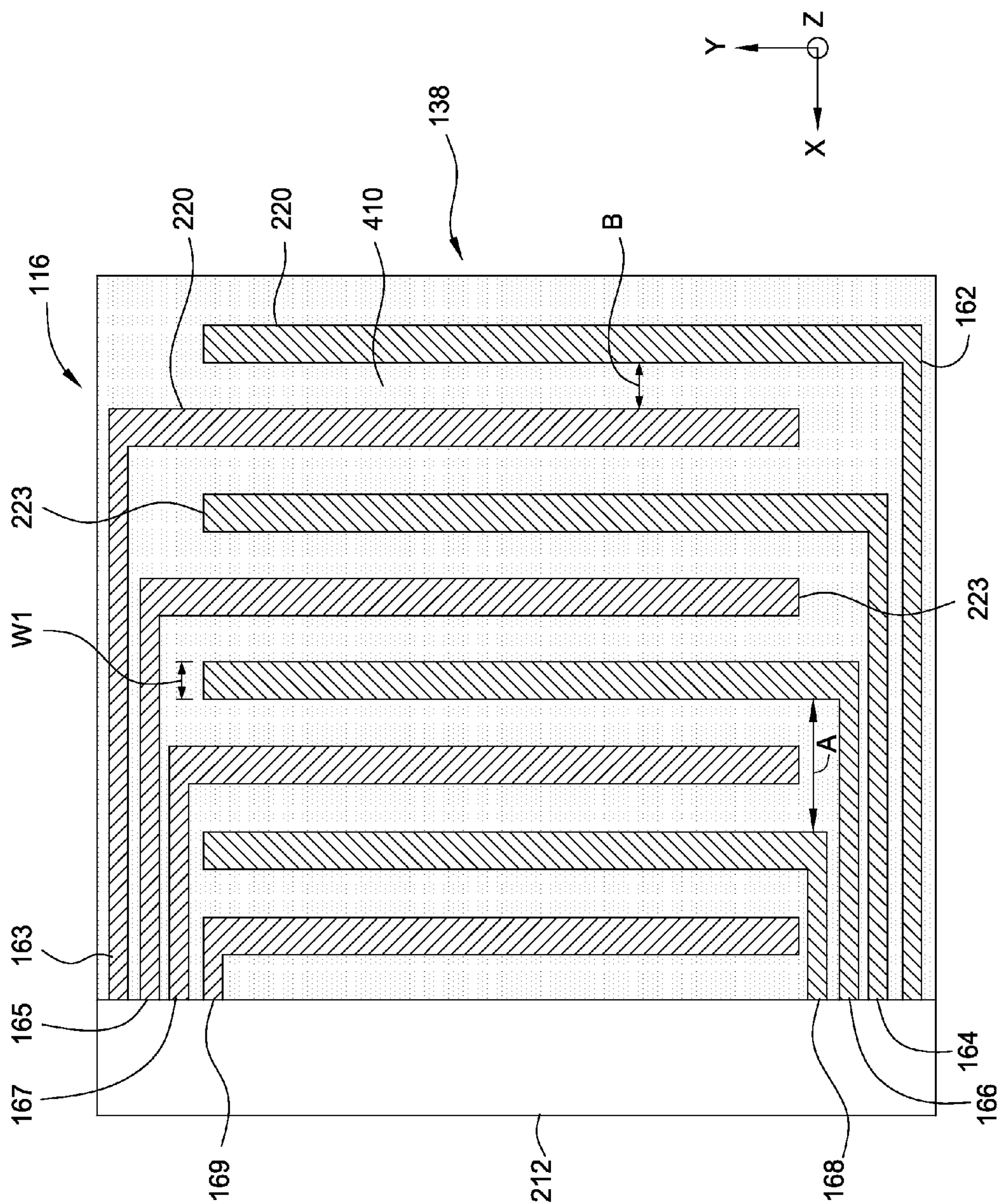

FIG. 4

FIG. 5A

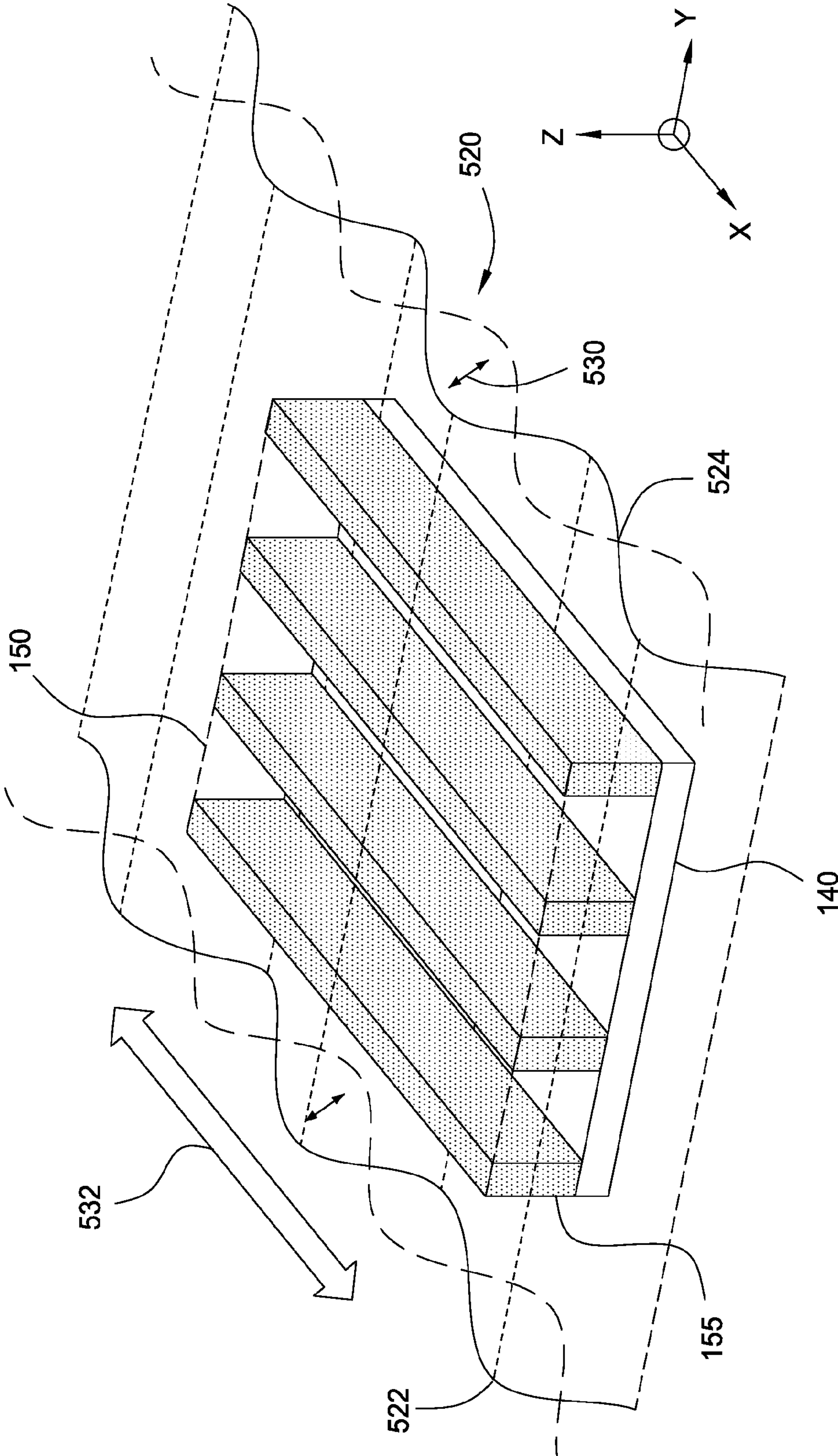

FIG. 5B

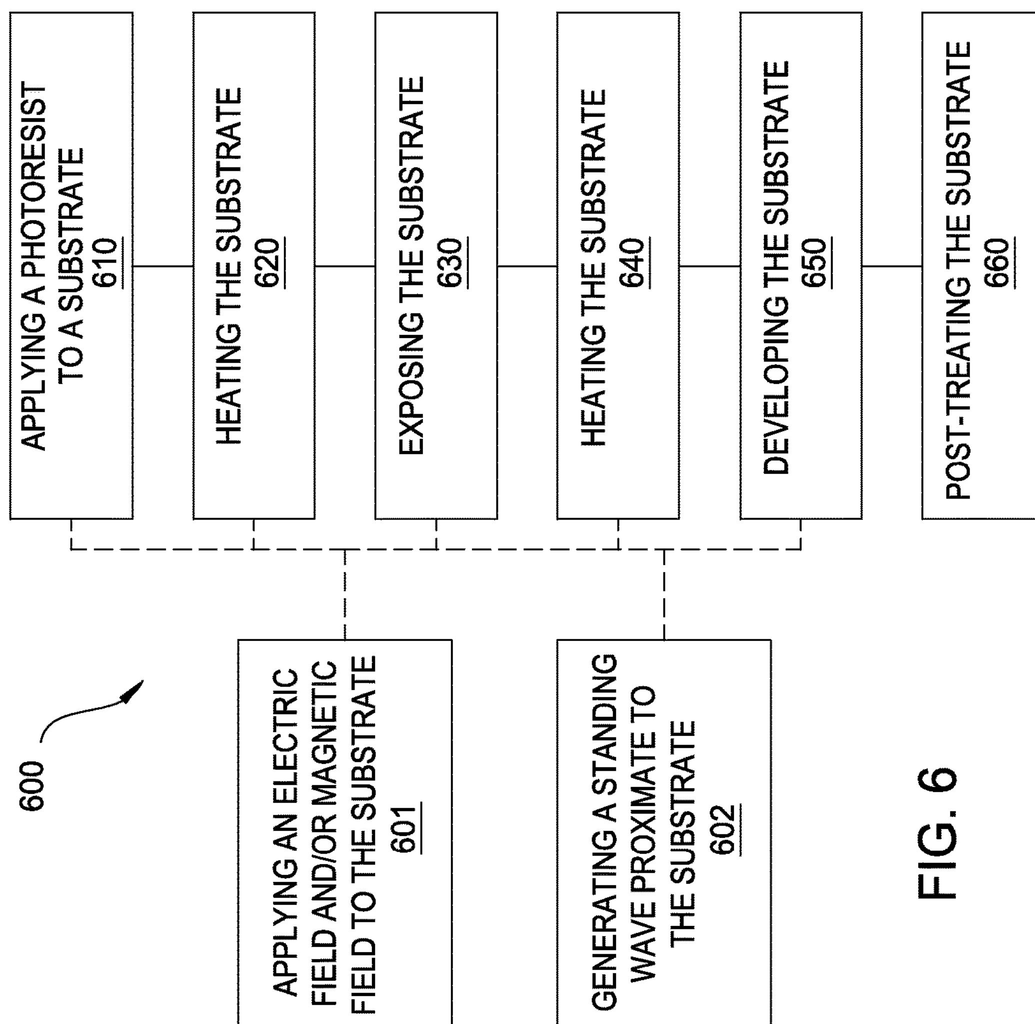

FIG. 6

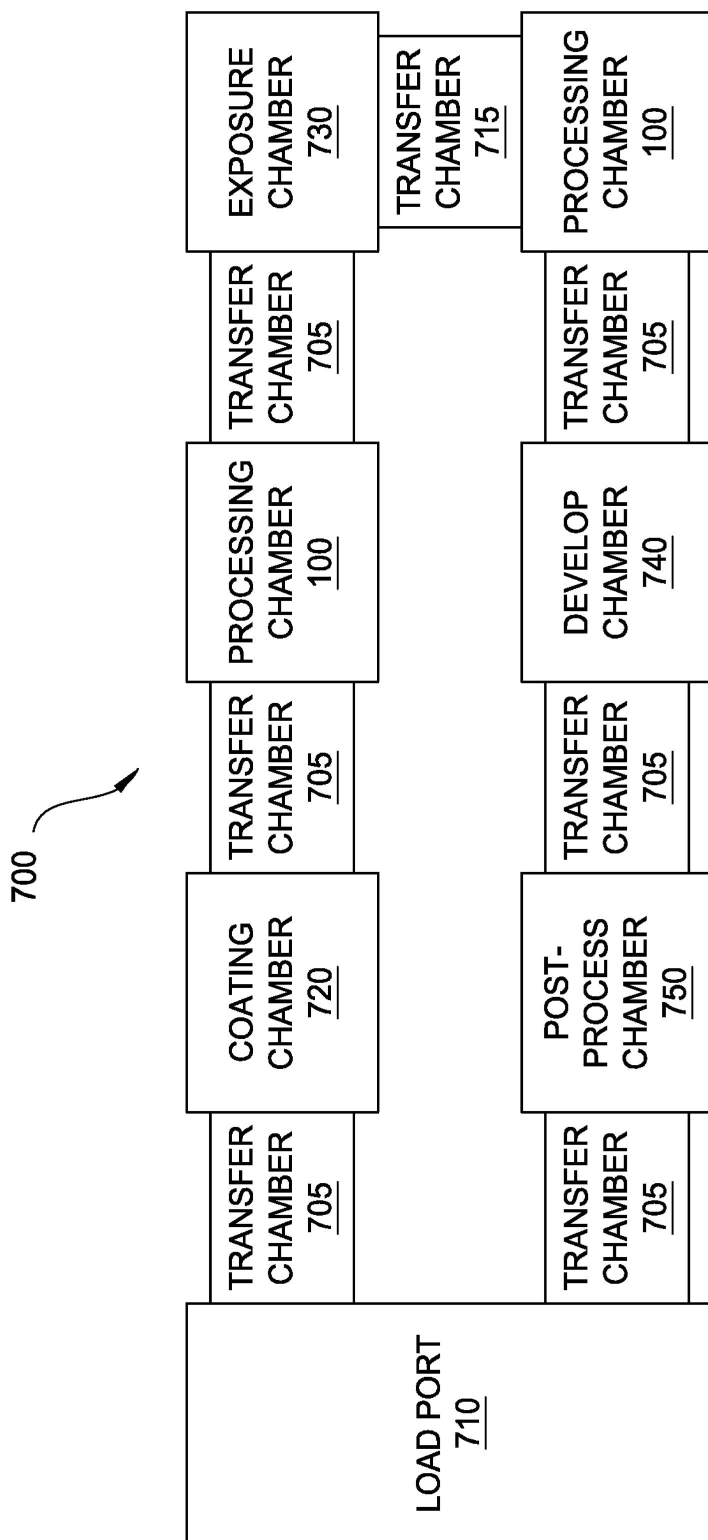

FIG. 7

CONTROLLING PHOTO ACID DIFFUSION IN LITHOGRAPHY PROCESSES

CROSS-REFERENCE TO RELATED APPLICATIONS

This application claims priority to U.S. Provisional Patent Application Ser. No. 62/023,106, filed on Jul. 10, 2014, which is hereby incorporated herein by reference.

BACKGROUND

Field

The present disclosure generally relates to methods and apparatuses for processing a substrate, and more specifically to methods and apparatuses for controlling photoresist line edge/width roughness.

Description of the Related Art

Integrated circuits have evolved into complex devices that can include billions 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 basic stages. First, a photoresist layer is formed on a substrate. The photoresist layer may be formed using a variety of techniques, such as spin-coating. A chemically-amplified photoresist may include a resist resin and a photoacid generator. Upon exposure to electromagnetic radiation during an exposure stage, the photoacid generator alters the solubility of the photoresist, enabling portions of the photoresist to be removed during a development stage. The electromagnetic radiation may have any suitable wavelength, such as a wavelength in the extreme ultraviolet (UV) range. Electromagnetic radiation may be generated using any suitable source, for example, via a 193 nm ArF laser, an electron beam, an ion beam, or another source. Excess solvent may then be removed during a pre-exposure bake stage.

During the exposure stage, a photomask or reticle may be used to selectively expose certain regions of the substrate to electromagnetic radiation. Other exposure methods may include maskless exposure methods. Exposure to electromagnetic radiation may cause the photoacid generator to release acids, creating a latent acid image in the resist resin. After exposure, the substrate may be heated in a post-exposure bake stage. During the post-exposure bake stage, acid released by the photoacid generator reacts with the resist resin, changing the solubility of the resist resin.

After the post-exposure bake, the substrate and, particularly, the photoresist layer may be developed and rinsed. After development and rinsing, the pattern of the mask is transferred to the substrate.

As processor architectures continue to evolve, higher circuit densities and lower leakage currents become more desirable. The demand for higher circuit densities necessitates a reduction in the dimensions of integrated circuit components. Accordingly, the lithography process must precisely transfer smaller and smaller features onto a substrate without causing damage to the substrate. In order to precisely and accurately transfer features onto a substrate, high-resolution lithography techniques may implement light sources that provide electromagnetic radiation having short wavelengths. Decreasing the wavelength of electromagnetic radiation used during lithography enables the minimum feature size of circuit components to be reduced. However, as the minimum feature size is reduced, the edge roughness of the photoresist layer typically becomes more difficult to control.

Therefore, there is a need for improved techniques for controlling line edge/width roughness.

SUMMARY

In one embodiment, an apparatus for processing a substrate includes a substrate support, a heat source, and an electrode assembly. The substrate support includes a surface configured to support a substrate thereon. The heat source is configured to heat a substrate positioned on the surface of the substrate support. The electrode assembly is positioned proximate to the surface of the substrate support. The electrode assembly includes a plurality of individually addressable electrodes, each individually addressable electrode including one or more antennas. The electrode assembly is configured to generate an electric field in a direction substantially parallel to the surface of the substrate support.

In another embodiment, a method of processing a substrate includes applying a photoresist layer that includes a photoacid generator to a substrate. The method further includes exposing portions of the photoresist layer to electromagnetic radiation to form substantially parallel lines of material in the photoresist layer having different chemical properties than the portions of the photoresist layer not exposed to the electromagnetic radiation. The method further includes heating the substrate after exposing the substrate, and applying an electric field to the substrate in a direction parallel to the direction of the lines with an electrode assembly positioned proximate to the substrate. The electrode assembly includes a plurality of individually addressable electrodes, each individually addressable electrode including one or more antennas. The electric field is applied during the heating.

In yet another embodiment, an apparatus for processing a substrate includes a substrate support, a heat source, a cavity, and at least one generator. The substrate support includes a surface configured to support a substrate thereon. The heat source is configured to heat a substrate positioned on the surface of the substrate support. The cavity is positioned proximate to the surface of the substrate support. The at least one generator is proximate to the cavity and configured to generate a standing wave within the cavity.

In yet another embodiment, a method of processing a substrate includes applying a photoresist layer that includes a photoacid generator to a substrate. The method further includes exposing portions of the photoresist layer to electromagnetic radiation to form substantially parallel lines of material in the photoresist layer having different chemical properties than the portions of the photoresist layer not exposed to the electromagnetic radiation. The method further includes heating the substrate after exposing the substrate, and generating a standing wave proximate to the substrate.

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 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.

FIG. **1** is a schematic cross-sectional view of an apparatus for processing a substrate.

FIG. **2** is a top view of one embodiment of the electrode assembly and photoresist layer of FIG. **1**.

FIG. **3** is a top view of another embodiment of the electrode assembly and photoresist layer of FIG. **1**.

FIG. **4** is a top view of an embodiment in which the electrode assembly is proximate to, or integrated with, the substrate support structure of FIG. **1**.

FIG. **5**A is a cross-sectional view of a cavity in which the substrate may be disposed.

FIG. **5**B is a perspective view of a standing wave that may be generated proximate to the photoresist layer of FIG. **1**.

FIG. **6** is a flow diagram of representative methods of processing a substrate.

FIG. **7** illustrates one representative processing system that may be used to process a substrate according to embodiments disclosed herein.

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

Methods and apparatuses for minimizing line edge/width roughness in lines formed by photolithography are provided. The random diffusion of acid generated by a photoacid generator during a post-exposure bake procedure contributes to line edge/width roughness. Methods disclosed herein apply an electric field and/or a magnetic field during photolithography processes. The application of an electric field, a magnetic field, and/or a standing wave controls the diffusion of acid along the line and spacing direction, reducing line edge/width roughness that may result from random diffusion. Apparatuses for carrying out the aforementioned methods are also disclosed herein.

FIG. **1** is a schematic cross-sectional view of an apparatus for processing a substrate, according to one embodiment. As shown in the embodiment of FIG. **1**, the apparatus may be in the form of a vacuum processing chamber **100**. In other embodiments, the processing chamber **100** may not be coupled to a vacuum source.

The processing chamber **100** may be an independent processing chamber. Alternatively, the processing chamber **100** may be part of a processing system, such as, for example, an in-line processing system, a cluster processing system, or the track processing system shown in FIG. **7**. FIG. **7** illustrates one representative processing system **700** that may be used to process a substrate according to embodiments disclosed herein. The processing system **700** includes a load port **710**, a coating chamber **720**, a processing chamber **100**, an exposure chamber **730** (such as a scanner), a second processing chamber **100**, a development chamber **740**, and a post-process chamber **750**. Each chamber of the processing system **700** is coupled to each adjacent chamber by a transfer chamber **705** or a transfer chamber **715**. The transfer chambers **705** and the transfer chamber **715** may be substantially similar or different.

The load port **710** may be used to introduce or remove substrates into or out of the processing system **700**. The coating chamber **720** may be used, for example, for applying a photoresist to a substrate. The coating chamber **720** may be, for example, a spin coater. The exposure chamber **730** 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 **740** may be used, for example, for removing portions of the photoresist layer. The post-process chamber **750** may be used, for example, to perform a variety of post-processing steps on a substrate. The processing chamber **100** is described in detail below and may be used for a pre-exposure bake, a post-exposure bake, and/or other processing steps. As described below, the processing chamber **100** may include an electrode assembly **116** and/or a cavity **502** (e.g., an electromagnetic cavity or optical cavity). However, it is to be understood that the coating chamber **720**, the exposure chamber **730**, and the development chamber **740** may also include an electrode assembly **116** and/or a cavity **502**.

The processing chamber **100** includes chamber walls **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 walls **102** partially enclose a processing volume **112**. The processing volume **112** is accessed through a substrate transfer port (not shown) configured to facilitate movement of a substrate **140** into and out 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.

A pumping port **114** may optionally be disposed through one of the lid assembly **110**, sidewalls **106** or bottom **108** of the processing chamber **100** to couple the processing volume **112** to an exhaust port. The exhaust port couples the pumping port **114** to various vacuum pumping components, such as a vacuum pump. 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**. The processing chamber **100** may be coupled to one or more supply sources **104** for delivering one or more source compounds into the processing volume **112**.

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 comprise an aluminum body **124** that encapsulates at least one embedded heater **132**. In some embodiments, the substrate support assembly **138** may be an electrostatic chuck. The electrostatic chuck may have one or more temperature zones for uniform control of temperature on the wafer. In other embodiments, the substrate support assembly **138** may be a vacuum chuck that secures the wafer. The heater **132**, such as a resistive element, is disposed in the substrate support assembly **138**. The heater **132** controllably heats the substrate support assembly **138** and the substrate **140** positioned thereon to a predetermined temperature. The heater **132** is configured to quickly ramp the temperature of the substrate **140** and to accurately control the temperature of the substrate **140**. In some embodiments, the heater **132** is connected to and controlled by the power source **174**. The power source **174** may alternatively or additionally apply power to the substrate support assembly **138**. The power source **174** may be configured similarly to the power source **170**, discussed below.

In some embodiments, the substrate support assembly **138** may be configured to rotate. In some embodiments, the substrate support assembly **138** is configured to rotate about the z-axis. The substrate support assembly **138** may be configured to continuously or constantly rotate, or the substrate support assembly **138** may be configured to rotate in a step manner. For example, the substrate support assembly **138** may rotate a predetermined amount, such as 90°, 180°, or 270°, and then rotation may stop for a predetermined amount of time.

In other 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 other embodiments, one or more lasers may be used to heat a photoresist layer **150** (or other layer) positioned on the substrate **140** and/or the antennas **220** and **221** of the electrode assembly **116**. In other 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 a substrate **140** positioned on the substrate support assembly **138**.

Generally, the substrate support assembly **138** has a first surface **134** and a second surface **126**. The first surface **134** is opposite the second surface **126**. The first surface **134** is configured to support the substrate **140**. The second surface **126** has a stem **142** coupled thereto. The substrate **140** is positioned on the first surface **134** of the substrate support assembly **138**. In some embodiments, the substrate support assembly **138** includes a cavity in which the substrate **140** may be positioned.

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. In other embodiments, the substrate **140** may have more than one layer **145**. The substrate **140** also has a photoresist layer **150** disposed over the layer **145**. The substrate **140** has been previously exposed to electromagnetic radiation in an exposure stage of a photolithography process. The photoresist layer **150** has latent image lines **155** formed therein from 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.

The first surface **134** of the substrate support assembly **138** may be separated from the electrode assembly **116** by a distance d in the z-direction. 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. The separation may be enabled by moving the stage, by moving the electrode, or by moving both. The lift system may accurately and precisely control the position of the substrate **140** in the z-direction. 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.

The lid assembly **110** may optionally include an inlet **180** through which gases provided by the 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, other gases, or combinations thereof. The gases from the supply sources **104** may create a controlled environment within the processing chamber **100**. An actuator **190** may be optionally coupled between the lid assembly **110** and the electrode assembly **116**. The actuator **190** is 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 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**. In still other embodiments, the electrode assembly **116** may be embedded between the first surface **134** and the second surface **126** of the substrate support assembly **138**.

The electrode assembly **116** may include plurality of electrodes, such as a first electrode **158** and a second electrode **160**. As shown, the first electrode **158** is coupled to a power supply **170**, and the second electrode **160** is coupled to an optional power supply **175**. In other embodiments, one of the first electrode **158** and the second electrode **160** may be coupled to a power supply and the other electrode may be coupled to a ground. In some embodiments the first electrode **158** and the second electrode **160** are coupled to a ground and the power supply **174** delivers power to the substrate support and is a bipolar power supply that switches between a positive and negative bias. In some embodiments, the power supply **170** or the power supply **175** may be coupled to both the first electrode **158** and the second electrode **160**. In other embodiments, the power supply **170** or the power supply **175** may be coupled to the first electrode **158**, the second electrode **160**, and the substrate support assembly **138**. In such embodiments, the pulse delay to each of the first electrode **158**, the second electrode **160**, and the substrate support assembly **138** may be different. The electrode assembly **116** may be configured to generate an electric field parallel to the x-y plane defined by the first surface 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.

The power supply **170** and the power supply **175** are configured to supply, for example, between about 500 V and about 100 kV to the electrode assembly **116**. In some embodiments, the power supply **174** may also be configured to provide power to the electrode assembly **116**. In some embodiments, any or all of the power supply **170**, the power supply **174**, or the power supply **175** are a pulsed direct current (DC) power supply. The pulsed DC wave may be from a half-wave rectifier or a full-wave rectifier. The power supply **170**, the power supply **174**, and/or the power supply **175** 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 may be from 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 may be between about 20% and about 40%. In other embodiments, 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 embodiments, the rise and fall time of the pulsed DC power may be between about 10 ns and about 100 ns. In some embodiments, the rise and fall time of the pulsed DC power may be about 500 ns. In some embodiments, any or all of the power supply **170**, the power supply **174**, and the power supply **175** are an alternating current power supply. In other embodiments, any or all of the power supply **170**, the power supply **174**, and the power supply **175** are a direct current power supply.

In some embodiments, any or all of the power supply **170**, the power supply **174**, and the power supply **175** 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. In some embodiments, the first electrode **158** and the second electrode **160** are pulsed negatively while the substrate support assembly is also pulsed negatively. In these embodiments, the first electrode **158** and the second electrode **150** are the substrate support assembly **138** are synchronized but offset. For example, the first electrode **158** may be at the "one" state while the substrate support assembly is at the "zero" state," then the substrate support assembly **138** in the one state while the first electrode **158** is at the zero state.

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%, the width of the substrate support assembly **138**. In embodiments where the electrode assembly **116** is less wide than 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**.

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**. The magnets **196** may be, for example, permanent magnets or electromagnets. Representative permanent magnets include ceramic magnets and rare earth magnets. In embodiments where the magnets **196** include electromagnets, the magnets **196** may be coupled to a power source (not shown). The magnets **196** are configured to generate a magnetic field in a direction perpendicular or parallel to the direction of the electric field lines generated by the electrode assembly **116** at the first surface **134** of the substrate support assembly **138**. For example, the magnets **196** may be configured to generate a magnetic field in the x-direction when the electric field generated by the electrode assembly **116** is in the y-direction. The magnetic field drives the charged species **255** (shown in FIG. **2**) and polarized species (not shown) generated by the photoacid generators in the photoresist layer **150** in a direction perpendicular to the magnetic field, such as the direction parallel with the latent image lines **155**. By driving the charged species **255** and polarized species in a direction parallel with the latent image lines **155**, line roughness may be reduced. The uniform directional movement of the charged species **255** and polarized species is shown by the double headed arrow **270** in FIG. **2**. In contrast, when a magnetic field is not applied, the charged species **255** and polarized species may move randomly, as shown by the arrows **270'**.

Continuing to refer to FIG. **2**, the electrode assembly **116** includes at least the first electrode **158** and the second electrode **160**. The first electrode **158** includes a first terminal **210**, a support structure **230**, and one or more antennas **220**. The second electrode **160** includes a first terminal **211**, a support structure **231**, 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 **158** may form a unitary body. Alternatively, the first electrode **158** 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 **160** may similarly be a unitary body or be comprised of separate detachable components. The first electrode **158** and the second electrode **160** may be prepared by any suitable means. For example, the first electrode **158** and the second electrode **160** may be fabricated by machining, casting, or additive manufacturing.

The support structure **230** may be made from a conductive material, such as metal. For example, the support structure **230** may be made of silicon, polysilicon, silicon carbide, molybdenum, aluminum, copper, graphite, silver, platinum, gold, palladium, zinc, other materials, or mixtures thereof. The support structure **230** may have any desired dimensions. For example, the length L 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 approximately equal to a diameter of a standard semiconductor substrate. In other embodiments, the support structure **230** has a length L that is larger or smaller than the diameter of a standard semiconductor substrate. For example, in different representative embodiments, the length L 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. The width W of the support structure **230** may be between about 2 mm and about 25 mm. In other embodiments, the width W of the support structure **230** is less than about 2 mm. In other embodiments, the width W of the support structure **230** is 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 some embodiments, the support structure **230** may be square, cylindrical, rectangular, oval, rods, or other shapes. Embodiments having round exterior surfaces may avoid arcing.

The support structure **231** may be made of the same materials as the support structure **230**. The range of dimensions suitable for the support structure **230** is also suitable for the support structure **231**. In some embodiments, the support structure **230** and the support structure **231** are made of the same material. In other embodiments, the support structure **230** and the support structure **231** are made of different materials. The lengths L, widths W, 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 **158** 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**. The one or more antennas **220** of the first electrode **158** may have any desired dimensions. For example, a length L**1** of the one or more antennas **220** 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**1** approximately equal to the diameter of a standard substrate. In other embodiments, the length L**1** of the one or more antennas **220** may be between about 75% and 90% of the diameter of a standard substrate. A width W**1** of the one or more antennas **220** may be between about 2 mm and about 25 mm. In other embodiments, the width W**1** of the one or more antennas **220** is less than about 2 mm. In other embodiments, the width

W1 of the one or more antennas **220** is greater than about 25 mm. The thickness of the one or more antennas **220** may be between about 1 mm and about 10 mm, such as between about 2 mm and about 8 mm. The one or more antennas **220** may have a cross-section that is square, rectangular, oval, circular, cylindrical, or another shape. Embodiments having round exterior surfaces may avoid arcing.

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**. For example, some of the one or more antennas **220** may have different lengths L**1** than one or more of the other antennas **220**. Each of the one or more antennas **220** may be made of the same material. In other embodiments, some of the antennas **220** may be made of a material different than that 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**. In some embodiments, the antennas **220** and the antennas **221** are made of the same material. In other embodiments, the antennas **220** and the antennas **221** are made of different materials. The lengths L**1**, widths W**1**, and thicknesses of the antennas **220** and the antennas **221** may be the same or different.

The antennas **220** may include between 1 and about 40 antennas **220**. For example, the antennas **220** may include between about 4 and about 40 antennas **220**, such as between about 10 and about 20 antennas **220**. In other embodiments, the antennas **220** may include more than 40 antennas **220**. In some embodiments, each of the antennas **220** may be substantially perpendicular to the support structure **230**. For example, in embodiments where the support structure **230** is straight, each antenna **220** may be substantially parallel to the support structure **230**. 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**.

Each of the antennas **220** may be substantially parallel to each of the antennas **221**. In some embodiments, at least one of the antennas **220** is substantially parallel with at least one of the antennas **221**. Each of the antennas **220** may be vertically aligned with each of the antennas **221**. In some embodiments, at least one of the antennas **220** is vertically aligned with at least one of the antennas **221**.

The support structure **230** and the support structure **231** are straight. In other embodiments the support structure **230** and the support structure **231** may not be straight. For example, the support structure **230** and the support structure **231** may be 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**. In these embodiments, each of the antennas **221** may be substantially parallel to each of the other antennas **221**.

Each of the antennas **220** has a terminal end **223**. Each of the antennas **221** has 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. In other embodiments, the distances C and C' may be less than about 1 mm or greater than about 10 mm. In some embodiments, the distance C and the distance C' are equal. In other embodiments, the distance C and the distance C' are different.

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. For example, the distances A and A' may be between about 6 mm and about 20 mm, such as between about 10 mm and about 15 mm. The distances A and A' between each adjacent antennas **221**, **220** may be the same or different. For example, the distances A' between the first and second, second and third, and third and fourth antennas of the one or more antennas **220** may be different. In other embodiments, the distances A' may be the same.

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. For example, the distance B may be between about 2 mm and about 10 mm, such as between about 4 mm and about 6 mm. The distance B defined between may be the same, each distance B may be different, or some distances B may be the same and some distances B may be different. Modifying the distance B allows for easy control of the electric field strength.

The antennas **220**, **221** may be oriented in an alternating arrangement above the photoresist layer **150**. For example, the antennas **220** of the first electrode **158** and the antennas **221** of the second electrode **160** may be positioned such that at least one of the antennas **220** is positioned between two of the antennas **221**. Additionally, at least one antenna **221** may be positioned between two of the antennas **220**. In some embodiments, all but one of the antennas **220** is positioned between two of the antennas **221**. In those embodiments, all but one of the antennas **221** may be positioned between two of the antennas **220**. In some embodiments, the antennas **220** and the antennas **221** may each have only one antenna.

In some embodiments, the first electrode **158** has a first terminal **210**, and the second electrode **160** has a second terminal **211**. The first terminal **210** may be a contact between the first electrode **158** and the power supply **170**, the power supply **175**, or a ground. The second terminal **211** may be a contact between the second electrode **160** and the power supply **170**, the power supply **17**, or a ground. The first terminal **210** and the second terminal **211** are shown as being at one end of the first electrode **158** and the second electrode **160**, respectively. In other embodiments, the first terminal **210** and the second terminal **211** may be positioned at other locations on the first electrode **158** and the second electrode, respectively. The first terminal **210** and the second terminal **211** have different shapes and sizes than the support structure **230** and the support structure **231**, respectively. In other embodiments, the first terminal **210** and the second terminal **211** may have generally the same shapes and sizes as the support structure **230** and the support structure **231**, respectively.

In operation, a voltage may be supplied from a power supply, such as the power supply **170**, the power supply **174**, or the power supply **175**, to the first terminal **210**, the second terminal **211**, and/or the substrate support assembly **138**. 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 assembly **138**. The substrate **140** is positioned on the first surface **134** 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 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'**.

FIG. **3** is a top view of another embodiment of the electrode assembly **116** and photoresist layer **155** of FIG. **1**. As shown, the electrode assembly **116** may include a plurality of individually addressable electrodes **161**, including electrodes **162** through **169**. Each of the individually addressable electrodes **161** may be independently coupled to one or more power supplies via a controller **212**. For example, electrode **162** may include an antenna **220** that is coupled to power supply **170** and/or power supply **175** via the controller **212**, enabling the polarity of electrode **162** to be controlled independently from the polarities of electrodes **163** through **169**. Similarly, electrode **163** may include an antenna **220** that is coupled to power supply **170** and/or power supply **175** via the controller **212** or via a separate controller (not shown) from the controller **212** that is coupled to the electrode **162**. As such, the polarity of electrode **163** may be controlled independently from the polarities of electrode **162** and electrodes **164** through **169**.

Although each of the individually addressable electrodes **161** shown in FIG. **3** includes a single antenna **220**, in other embodiments, one or more of the individually addressable electrodes **161** may include more than one antenna **220**. For example, in other embodiments, electrode **162** may include two or more antennas **220**, each of which is driven with the same polarity during processing of a substrate **140**.

The antennas **220** associated with the individually addressable electrodes **161** may be driven according to any of the techniques described above in conjunction with FIG. **2**. In some embodiments, the controller **212** may be configured to independently switch one or more of the individually addressable electrodes **161** between a positive bias, a negative bias, and/or ground according to a predetermined pattern (e.g., an alternating pattern, sequentially, etc.) and/or as a function of time. For example, a positive bias (or negative bias) may be applied to each of electrodes **162** through **169**, in a sequential manner, in order to drive a charged species **255** to the left (i.e., in the x-direction) relative to the orientation shown in FIG. **3**. In other embodiments, two or more individually addressable electrodes **161** may be driven with a positive bias, driven with a negative bias, and/or coupled to ground in a coordinated manner, according to any useful pattern, to drive charged species **255** in one or more directions. For example, a positive bias (or negative bias) may be applied in a sequential manner to each of electrodes **162**, **164**, **166** and **168** while a negative bias (or positive bias) is applied to each of electrodes **163**, **165**, **167** and **169** in order to drive charged species **255** in a particular direction. In some embodiments, a first set of electrodes included in the plurality of individually addressable electrodes **161** may be driven according to a first pattern while a second set of electrodes included in the plurality of individually addressable electrodes **161** are driven according to a second pattern.

FIG. **4** is a top view of an embodiment in which the electrode assembly **116** is proximate to, or integrated with, the substrate support structure **138** of FIG. **1**. As shown, the individually addressable electrodes **161** may be disposed on or integrated with the substrate support structure **138**, such that an electric field is applied from the backside of the substrate **140**. In such embodiments, the individually addressable electrodes **161** may be coupled to power source **174** or to another power supply (e.g., power supply **170** or power supply **175**).

The individually addressable electrodes **161** may be positioned proximate to the first surface **134** of the substrate support **138** such that the substrate **140** is placed on top of the individually addressable electrodes **161** during processing. In other embodiments, the individually addressable electrodes **161** may be positioned proximate to the second surface **126**, for example, below the substrate support structure **138**. In still other embodiments, the individually addressable electrodes **161** may integrated with the substrate support structure **138** and positioned between the first surface **134** and the second surface **126**.

In embodiments in which the electrode assembly **116** is disposed on top of or integrated with the substrate support structure **138**, a dielectric material **410**, such as a ceramic, may be disposed between the antennas **220** of the individually addressable electrodes **161**. In such embodiments, the individually addressable electrodes **161** and dielectric material **410** may form a surface on which the substrate **140** can be positioned during processing. In other embodiments, no material is disposed between the antennas **220** of the individually addressable electrodes **161**. In the same or other embodiments, instead of disposing a dielectric material **410** between the antennas **220** of the individually addressable electrodes **161**, a vacuum may be generated between the antennas **220** during processing of the substrate **140**.

When the electrode assembly **116** is positioned below the substrate **140**, an electric field may be applied to the photoresist layer **150** by scanning the electrode assembly **116**. In some embodiments, the electrode assembly **116** may be moved relative to the photoresist layer **150** (e.g., by moving the electrode assembly **116** and/or photoresist layer **150**) while an electric field is generated by the electrode assembly **116**. In other embodiments, the photoresist layer **150** and electrode assembly **116** may remain stationary while one or more of the antennas **220** included in the electrode assembly **116** are driven—using any of the patterns or techniques described above—in order to move the charged species **255** in one or more directions. In such embodiments, the number of moving parts within the processing chamber **100** may be reduced while still enabling the electrode assembly **116** to scan the electric field relative to the photoresist layer **150**. In still other embodiments, an electrode assembly **116** including the two-terminal design shown in FIG. **2** may be disposed below the substrate **140** and/or integrated with the substrate support structure **138**.

FIG. **5**A is a cross-sectional view of a cavity **502** in which the substrate **140** may be disposed. FIG. **5**B is a perspective view of a standing wave **520** that may be generated proximate to the photoresist layer **150** of FIG. **1**. In various embodiments, the cavity **502** may be positioned above or integrated with the substrate support structure **138**. The cavity **502** includes one or more generators **510** that are configured to generate a standing wave **520** inside of the cavity **502**. The standing wave **520** may include nodes **522** and antinodes **524**.

Generating a standing wave **520** proximate to the photoresist layer **150** may enable charged species **255** included in

the photoresist layer **150** to be driven in one or more directions. In some embodiments, at least a portion of the standing wave **520** extends into the photoresist layer **150**. However, the standing wave **520** may be generated at any location with respect to the substrate **140** and/or photoresist layer **150**. In general, the standing wave **520** drives the charged species **255** generated by the photoacid generator in one or more directions that are parallel to the direction of the latent image lines **155**. For example, oscillation **530** of the nodes **522** may cause the charged species **255** to move along the z-direction. In some embodiments, the phase of the standing wave **520** may be varied in order to generate movement **532** of the standing wave **520** along the x-direction. In other embodiments, one or more generators **510** may be used to generate non-standing waves proximate to the photoresist layer **150**.

Standing waves **520** may be generated within the cavity **502** using any practical means. The wavelength(s) generated by the generator(s) **510** may depend upon the composition of the photoresist layer **150**. For example, the wavelength(s) generated by the generator(s) **510** may be selected such that the direction of the charged species **255** may be controlled without further exposing the photoresist layer **150** (e.g., without substantially altering the latent acid image in the photoresist layer **150**). In some embodiments, the one or more generators **510** generate standing waves **520** using wavelengths in the radiofrequency range. In such embodiments, wavelengths that are greater than approximately 5 centimeters (i.e., frequencies of less than about 6 GHz) may be used. For example, the generator(s) **510** may be microwave generators and/or long-wavelength lasers, such as an infrared laser or CO_2 laser (e.g., running at a wavelength of about 1550 nm). In some embodiments, the period D of the resulting standing wave **520** may be approximately 10 to 5000 nanometers, such as approximately 100 to 500 nanometers.

Standing waves **520** may be used to control the direction in which charged species **255** move in addition to, or instead of, controlling the direction of the charged species **255** by generating electric fields and/or magnetic fields, as described above. When these techniques are used in conjunction with one another, the electrode assembly **116** may be disposed above or below the substrate support structure **138**, and a standing wave **520** may be generated within a cavity **502** that is disposed on or integrated with the substrate support structure **138**. Additionally, the electrode assembly **116** may be integrated with the substrate support structure **138**, as illustrated in FIG. **4**, and standing waves **520** may be generated above (e.g., on top of) the electrode assembly **116**.

FIG. **6** is a flow diagram of a representative method **600** of processing a substrate **140**. The method **600** for processing the substrate **140** has multiple stages. The stages can be carried out in any order or simultaneously (except where the context excludes that possibility), and the method **600** can include one or more other stages which are carried out before any of the defined stages, between two of the defined stages, or after all the defined stages (except where the context excludes that possibility). Not all embodiments include all the stages.

In general, the methods **600** include a stage **610**. Stage **610** includes applying a photoresist containing a photoacid generator to a substrate **140**. The methods **600** may also include stage **620**. Stage **620** includes heating the substrate **140** in a pre-exposure bake. In general, the methods **600** also include stage **630**. Stage **630** includes exposing the substrate **140** to electromagnetic radiation. The methods **600** may further include stage **640**. Stage **640** includes heating the substrate **140** in a post-exposure bake. The methods **600** may also include stage **650** and stage **660**. Stage **650** and stage **660** include developing the substrate **140** and post-treating the substrate **140**, respectively.

In general, the method **600** may also include stage **601** and/or stage **602**. Stage **601** includes applying an electric and/or a magnetic field to the substrate **140** via the electrode assembly **116** (e.g., via the first electrode **158**, the second electrode **160**, and/or the individually addressable electrodes **161**). Stage **602** includes generating a standing wave proximate to the substrate **140**. In both stage **601** and stage **602**, the charged species **255** generated by the photoacid generator may be driven in one or more directions (e.g., the z-direction and/or the x-direction) that are parallel to the direction of the latent image lines **155** while the substrate is being heated. Stage **601** and stage **602** are described herein as occurring during the stage **640**. However, stage **601** and stage **602** may occur during any other stage or combination of stages.

At stage **610**, 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 via a spin coating apparatus. For example, the substrate **140** may be introduced into and positioned on a rotatable chuck of a spin coater. Thereafter, a solution containing the photoresist may be applied to the substrate **140** while the substrate **140** is rapidly spun, resulting in a uniform photoresist layer **150**.

In some embodiments, the spin coater may be part of a processing system, such as the processing system **700**. In embodiments in which the spin coater is part of the processing system **700**, the spin coater may be within the coating chamber **720**. In such embodiments, the substrate **140** may enter the processing system **700** through the load port **710** and thereafter be transferred to the coating chamber **720** through a transfer chamber **705**.

The spin coater may include electrode assembly **116**, which may be coupled to one or more power sources. For example, the electrode assembly **116** may be disposed in the coating chamber **720**. The substrate **140** may be positioned relative to the electrode assembly **116** such that the electrode assembly **116** produces an electric field parallel to the lateral dimensions of the substrate **140**. In some embodiments, the electrode assembly **116** may also be coupled to an actuator **190**. The spin coater may also include magnets **196**. The magnets **196** may be configured to generate a magnetic field in a direction perpendicular or parallel to the direction of the electric field lines generated by the electrode assembly **116**.

The photoresist 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, Novolac resins, poly(methylmethacrylates), and poly(olefin sulfones). Other photoresist resins may also be used.

Upon exposure to electromagnetic radiation, the photoacid generator generates charged species **255**, such as a 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 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.

At optional stage **620**, the substrate **140** may be heated in a pre-exposure bake. During the pre-exposure bake, the substrate **140** is heated to partially evaporate the photoresist solvents. The pre-exposure bake of stage **620** and the photoresist application of stage **610** may occur in the same chamber. For example, both stages may occur in a chamber that includes the spin coater. In one embodiment, both stages may occur in the coating chamber **720**. Alternatively, the substrate **140** may be transferred to a different processing chamber. For example, in an embodiment using the processing system **700**, the substrate **140** may be transferred from the coating chamber **720** to a processing chamber **100** through a transfer chamber **705**.

As noted above, the processing chamber **100** includes an electrode assembly **116**. The substrate **140** may be positioned in the processing chamber **100** relative to the electrode assembly **116** such that the electrode assembly **116** may produce an electric field parallel to the lateral dimensions of the substrate **140**. In some embodiments, the electrode assembly **116** of the processing chamber **100** may also be coupled to an actuator **190**. The processing chamber **100** may also include magnets **196**. The magnets **196** may be configured to generate a magnetic field in a direction perpendicular or parallel to the direction of the electric field lines generated by the electrode assembly **116**.

At stage **630**, the substrate **140** and portions of the photoresist layer **150** are exposed to electromagnetic radiation. Stage **630** may be performed in an exposure chamber. In one embodiment, after completion of stage **620**, the substrate **140** is transferred to an exposure chamber. In an embodiment using the processing system **700**, the substrate **140** may be transferred from the processing chamber **100** to the exposure chamber **730** through the transfer chamber **705**. The exposure chamber may also include an electrode assembly **116** coupled to one or more power sources and/or an actuator **190** and magnets **196**. The substrate **140** may be positioned in the exposure chamber relative to the electrode assembly **116** and magnets **196** as described in relation to the coating chamber **720**.

In stage **630**, 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. The acid generated by the photoacid generator results 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 spacings may be between about 10 nm and about 16 nm. In other embodiments the line widths and spacings 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**.

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.

At stage **640**, the substrate **140** is heated in a post-exposure bake process. In one embodiment, after the completion of stage **630**, the substrate **140** is transferred to a processing chamber. In some embodiments, the processing chamber may be the processing chamber **100**. In embodiments using the processing system **700**, the substrate **140** may be transferred from the exposure chamber **730** to the processing chamber **100** through the transfer chamber **715**. The substrate **140** may be positioned on the first surface **134** of the substrate support assembly **138**. The power source **174** may provide power to the embedded heater **132** to heat the substrate **140**. 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. The temperature of the substrate **140** and the photoresist layer **150** may be maintained at between about 70° C. and about 160° C., such as between about 90° C. and 140° C., during stage **640**. In other embodiments, the substrate **140** may be heated by a resistive heater, a heat lamp, a laser, or other heat source. In still other embodiments, the substrate **140** may be heated by more than one of the embedded heater **132**, the resistive heater, the heat lamp, the laser, and the other heat sources. In some embodiments, the power supply **170** and the power supply **175** may also heat the substrate **140**.

A heat lamp, laser, or other heat source may also heat the antennas **220** and the antennas **221**. For example, the heat lamp, laser, or other heat source may heat the antennas **220** and the antennas **221** to between about 70° C. and about 160° C., such as between about 90° C. and 140° C., during stage **340**. In some embodiments, the temperatures of the antennas **220** and the antennas **221** are controlled to substantially match the temperature of the substrate support assembly **138**. Matching the temperature of the substrate support assembly **138** to the temperature of the antennas **220** and the antennas **221** allows for more uniform control of the temperature of the photoresist layer **150** during stage **640**. During the post-exposure bake, photoacid generators in the photoresist layer **150** may continue to alter the chemical properties of the exposed portions of the photoresist layer **150**.

Optionally during stage **640**, the pressure of the processing chamber **100** may be reduced by a vacuum source. The processing volume **112** may be reduced, for example, by the vacuum pump coupled to the processing volume **112** through the pumping port **114**. In some embodiments, the pressure of the processing chamber **100** may be 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. Reducing the pressure may reduce or eliminate arcing during processing. In some embodiments, the pressure of the processing

chamber **100** is not reduced. By not reducing the pressure, heat from the heat sources may be more readily transferred to the substrate **140**. In some embodiments, the pressure in the processing volume **112** is reduced to a pressure between ambient pressure and 10^{-5} Torr.

During stage **640**, a field is applied to the photoresist layer **150** to drive the charged species **255** created by the photoacid generator in the direction of the latent image lines **155**. The field may be an electric field or both an electric and a magnetic field. An electric field may be applied to the photoresist layer **150**, for example, by the electrode assembly **116**. In some embodiments, the electrode assembly **116** and the photoresist layer **150** remain stationary with respect to each other while the electrode assembly **116** generates an electric field. In other embodiments, the electrode assembly **116** and the photoresist layer **150** move relative to each other while the electrode assembly **116** generates an electric field. Relative motion may, for example, allow the electric field to scan the surface of the substrate **140**. As discussed below, scanning the surface of the substrate **140** with an electric field may allow for higher throughput and more precise control of the application of the electric field to the substrate **140**. Scanning also allows for the application of a more uniform electric field to the substrate **140**, which allows for a more uniform line edge roughness reduction.

In some embodiments, the distance d between the substrate **140** and the electrode assembly **116** may be adjusted. For example, in the embodiment shown in FIG. **1**, the distance d may be adjusted by either the actuator **190** or by the lift system coupled to the substrate support assembly **138**. The actuator **190** may move the electrode assembly **116** towards the substrate **140**. Additionally or alternatively, the lift system coupled the substrate support assembly **138** may move the substrate **140** towards the electrode assembly **116**. In some embodiments, the distance d is between about 0.1 mm and about 100 mm. For example, the distance d may be between about 8 mm and about 14 mm. In other embodiments, the distance d is less than about 0.1 mm or greater than about 100 mm. Adjusting the distance d allows the strength of the electric field applied to the charged species **255** to be adjusted. A smaller distance d applies a stronger electric field to the charged species **255**. A stronger electric field may then enable better control of the direction in which the charged species **255** diffuses.

In embodiments where the electrode assembly **116** and the photoresist layer **150** remain stationary with respect to each other—such as when the electrode assembly **116** is disposed below the substrate **140**—the electrode assembly **116** may have lateral dimensions that are larger than or substantially the same as the lateral dimensions of the photoresist layer **150**. One such embodiment is illustrated in FIG. **4**. In other embodiments, the lateral dimensions of the electrode assembly **116** may be smaller than the lateral dimensions of the photoresist layer **150**. In one embodiment where the lateral dimensions of the electrode assembly **116** are smaller than the lateral dimensions of photoresist layer **150**, the electrode assembly **116** may be positioned over a specific region of the photoresist layer **150**. For example, the specific region of the photoresist layer **150** may be where at least some of the latent image lines **155** are transferred during stage **630**.

The electrode assembly **116** may generate an electric field in a direction along the length of the latent image lines **155**. In other words, the electrode assembly **116** may generate an electric field parallel to the latent image lines **155**. The generated electric field may have a field strength of, for example, between about 0.1 MV/m and about 100 MV/m, such as, between about 0.5 MV/m and about 10 MV/m. The electric field may be generated by, for example, the power supply **170**, the power supply **175**, and/or the power supply **174**. The power provided by the one or more power supplies may have the properties discussed above in relation to FIG. **1**. The above power conditions may allow for the charged species **255** to diffuse in the direction of the latent image lines **155** on the order of between about 10 nm and about 50 nm while limiting the diffusion perpendicular to the latent image lines **155** to less than about 5 nm. In some embodiments, the diffusion in the direction of the latent image lines **155** may be less than about 10 nm or greater than about 50 nm while the perpendicular diffusion is about 5 nm. In some embodiments, the pulsed DC power conditions allow for the electric field to act on the charged species **255** long enough to move the charged species **255** between about 10 nm and about 50 nm before switching the polarity. In other embodiments, the charged species may move less than about 10 nm or more than about 50 nm before switching polarity. In some embodiments, the power conditions provide a ratio of diffusion of the charged species **255** substantially along the direction of the latent image lines **155** to the diffusion of charged species **255** in a direction substantially perpendicular to the direction of the latent image lines **155** greater than about 5:1. For example, the ratio may be greater than about 10:1, such as greater than about 20:1. In some embodiments the ratio is between about 5:1 and about 20:1. In other embodiments, the ratio is between about 10:1 and about 20:1.

The power supply **170**, the power supply **174**, and/or the power supply **175** may continue to apply a voltage to the first terminal **210** and/or the second terminal **211** for a period of time. For example, the power supply may continue to supply the voltage for between about 30 seconds and about 180 seconds, such as between about 45 seconds and about 90 seconds, such as about 60 seconds. In other embodiments, the voltage may be applied for fewer than 30 seconds or more than 180 seconds. The length of time that the voltage is applied may depend on the photoresist layer **150** dimensions, the electrode assembly **116**, the amount of photoacid generator incorporated into the photoresist layer **150**, the electric field strength, and other variables. If the first terminal **210**, the second terminal **211**, or substrate support assembly **138** is not supplied power, the respective component may be connected to a ground.

The strength of the electric field applied to the photoresist layer **150** can be modified by varying several variables. For example, the electric field strength can be modified by the amount of voltage applied to the first terminal **210** and/or the second terminal **211**. In some embodiments, the electric field strength may also be controlled by varying the distance d between the electrode assembly **116** and the photoresist layer **150**. The electric field strength may also be modified by the dimensions of the electrode assembly **116**. For example, the dimensions A, B, and C may affect the strength of the electric field at the photoresist layer **150**.

In embodiments where the electrode assembly **116** and the photoresist layer **150** move relative to each other, the electrode assembly **116** and the photoresist layer **150** may have identical, substantially similar, or different lateral dimensions. In one embodiment, one of the lateral dimensions, such as the x-dimension, is at least substantially the same size as the x-dimension of the photoresist layer **150** and/or the substrate **140**. In that embodiment, the electrode assembly **116** may have a size in another lateral dimension, such as the y-dimension, that is smaller than the y-dimension photoresist layer and/or substrate **140**. In that embodiment, the relative movement between the electrode assembly **116**

and the photoresist layer **150** may be such that the x-dimension of the electrode assembly **116** moves relatively along the y-dimension of the photoresist layer **150**. The relative motion may result in the electrode assembly **116** scanning above the entirety or a portion of the surface of the photoresist layer **150**. Scanning may allow for higher throughput and for more precise control of the application of the electric field to the photoresist layer **150**. For example, in some embodiments, the pattern transferred to the photoresist layer **150** may have a first set of latent image lines **155** at a first location and a second set of latent image lines **155** at a second location. The first set of latent image lines **155** and the second set of latent image lines **155** may be oriented in different directions. Scanning may allow for an electric field to be applied to the first set of latent image lines **155** by the electrode assembly **116** such that the electric field is parallel to the first set of latent image lines **155**. Thereafter, the actuator **190** may move the electrode assembly **116** to the second location and orient the electrode assembly **116** so that the electric field generated by the electrode assembly is parallel to the second set of latent image lines **155**.

In another embodiment where the electrode assembly **116** is smaller than the photoresist layer **150**, both lateral dimensions of the electrode assembly **116** are smaller than the lateral dimensions of the photoresist layer **150**. In those embodiments, the electrode assembly **116** may scan the entirety or a portion of the surface of the photoresist layer **150**. In some embodiments where both lateral dimensions of the electrode assembly **116** are smaller than the lateral dimensions of the photoresist layer **150**, the electrode assembly **116** may have lateral dimensions sized to be substantially similar to the lateral dimensions of die on the substrate **140**. In those embodiments, the electrode assembly **116** may sequentially apply an electric field to each die or to only some of the die on the substrate **140**.

In one embodiment, the actuator **190** may provide the relative motion between the photoresist layer **150** and the electrode assembly **116**. In other embodiments, the substrate support assembly **138** may be configured to provide relative motion between the photoresist layer **150** and the electrode assembly **116**. In still other embodiments, both the actuator **190** and a movable substrate support assembly **138** may effectuate relative motion. In other embodiments, a substrate **140** may be positioned on a conveyor system, and the conveyor system may move the substrate **140** relative to one or more electrode assemblies **116**. The relative motion between the electrode assembly **116** and the photoresist layer **150** may have a velocity of between about 1 mm/sec and about 1000 mm/sec, such as between about 10 mm/sec and about 100 mm/sec, such as about 500 mm/sec. The velocity of relative motion may be adjusted to ensure that the photoresist layer **150** is exposed to the electric field for a time long enough to reduce the line edge/width roughness to the desired level. The velocity may depend on several variables, including the concentration of and identity of the photoacid generator and the composition of photoresist resin.

In some embodiments including relative motion between the electrode assembly **116** and the photoresist layer **150**, the distance d (z-direction) varies over time. Varying d during scanning alters the electric field strength, thus modulating the profile of the photoresist layer **150**. In other embodiments including relative motion disclosed herein, the substrate support assembly **138** rotates relative to the electrode assembly **116**. For example, the substrate support assembly **138** may rotate about the z-axis. The substrate support assembly **138** may be configured to continuously or constantly rotate, or the substrate support assembly **138** may be configured to rotate in a step manner. For example, the substrate support assembly **138** may rotate a predetermined amount, such as 90°, 180°, or 270°, and then rotation may stop for a predetermined amount of time. In other embodiments, the electrode assembly **116** rotates relative to the substrate support assembly **138**. The electrode assembly **116** may rotate in the same manner as the substrate support assembly **138**.

In embodiments including relative motion, the electric field may also be generated by any or all of the power supply **170**, the power supply **174**, and the power supply **175**. The properties of the applied voltage and power may be the same in embodiments including relative motion as in embodiments involving no relative movement. In scanning embodiments, the power may be applied for between about 30 seconds and about 360 seconds, such as between about 45 seconds and about 180 seconds, such as about 90 seconds. The length of time that the voltage is applied may depend on the photoresist layer **150** dimensions, the electrode assembly **116**, the amount of photoacid generator incorporated into the photoresist, the electric field strength, the rate of relative motion, and other variables. In embodiments including relative motion between the substrate **140** and the electrode assembly **116**, the relative motion may occur only while an electric field is applied, only while an electric field is not applied, or both while an electric field is applied and while an electric field is not applied. For example, in embodiments where the relative motion is caused by the rotation of the substrate support assembly **138**, the electric field may be applied during the rotation, the electric field may not be applied during the rotation, or the electric field may be applied both while the substrate support assembly **138** is rotating and not rotating.

In some embodiments, a magnetic field is generated in order to drive the charged species **255** in the direction of the latent image lines **155**. Magnets, such as the magnets **196**, may apply a magnetic field in a direction perpendicular or parallel to the latent image lines **155**, resulting in lines having a reduced line edge/width roughness. The magnets **196** may be, for example, permanent magnets or electromagnets. In other embodiments, the magnets **196** may be positioned elsewhere in the processing chamber **100** or outside the processing chamber **100**. The magnetic field strength at the photoresist layer **150** may be 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 photoresist layer **150** and the substrate **140**.

In some embodiments, the electrode assembly **116** generates and electric field and the magnets **196** generate a magnetic field. The electric field may be generated in the direction of the latent image lines **155** and a magnetic field may be generated in a direction perpendicular to the latent image lines **155**. In an embodiment including a magnetic field and an electric field the magnetic field may be perpendicular to the electric field.

Additionally, during stage **640**, standing waves **520** may be generated proximate to the substrate **140** in order to drive the charged species **255** in one or more directions that are parallel to the latent image lines **155**. For example, the oscillation **530** of a standing wave **520** may drive the charged species **255** along the z-direction and/or the phase of the standing wave **520** may be varied to drive the charged species **255** along the x-direction.

At optional stage **650**, the photoresist is developed. In one embodiment, after the completion of stage **640**, the substrate

140 is transferred to a development chamber. In embodiments using the processing system 700, the substrate 140 may be transferred from the processing chamber 100 to the development chamber 740 through the transfer chamber 705. The development chamber 740 may also include an electrode assembly 116 coupled to one or more power sources and/or an actuator 190 and magnets 196. The substrate 140 may be positioned in the development chamber 740 relative to the electrode assembly 116 and magnets 196 as described in relation to the coating chamber 720.

In stage 650, 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 Stoddard solvent. The substrate 140 may be rinsed with, for example, water or n-butylacetate. By stage 650, 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.

At optional stage 660, additional post-processing steps may be performed. The additional post-processing steps may be performed, for example, in a post-processing chamber. In an embodiment using the processing system 700, the substrate 140 may be transferred from the development chamber 740 through the transfer chamber 705 to the prost-processing chamber 750 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.

The previously described embodiments have many advantages, including the following. For example, the embodiments disclosed herein may reduce or eliminate line edge/width roughness. Additionally, the embodiments disclosed herein may allow for new fabrication process flows. The aforementioned advantages are illustrative and not limiting. It is not necessary for all embodiments to have all the advantages.

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.

What is claimed is:

1. An apparatus for processing a substrate, the apparatus comprising:
- a substrate support, the substrate support comprising a surface configured to support a substrate thereon;
- a heat source, the heat source configured to heat a substrate positioned on the surface of the substrate support; and
- an electrode assembly positioned proximate to the surface of the substrate support, the electrode assembly comprising a plurality of individually addressable electrodes, each individually addressable electrode comprising one or more antennas, wherein the electrode assembly is configured to generate an electric field in a direction substantially parallel to the surface of the substrate support.

2. The apparatus of claim 1, wherein the plurality of individually addressable electrodes comprises about 8 to about 80 individually addressable electrodes.

3. The apparatus of claim 1, wherein the electrode assembly is on the surface of the substrate support.

4. The apparatus of claim 1, wherein the electrode assembly is integrated with the substrate support.

5. The apparatus of claim 1, wherein the antennas associated with the plurality of individually addressable electrodes are substantially parallel to each other.

6. The apparatus of claim 5, wherein the distance between each adjacent antenna included in the plurality of individually addressable electrodes is substantially the same.

7. The apparatus of claim 6, wherein the substrate support and electrode assembly are positioned within a vacuum chamber.

8. The apparatus of claim 1, further comprising:
- a cavity positioned proximate to the surface of the substrate support; and
- at least one generator proximate to the cavity and configured to generate a standing wave within the cavity.

9. The apparatus of claim 8, wherein the at least one generator is configured to generate a frequency of less than about 6 GHz.

10. The apparatus of claim 8, wherein the at least one generator is configured to generate a standing wave having a period of about 100 nanometers to about 500 nanometers.

11. The apparatus of claim 8, wherein the at least one generator comprises at least one of a microwave generator and a long-wavelength laser.

12. An apparatus for processing a substrate, the apparatus comprising:
- a substrate support, the substrate support comprising a surface configured to support a substrate thereon;
- a heat source, the heat source configured to heat a substrate positioned on the surface of the substrate support;
- an electrode assembly positioned proximate to the surface of the substrate support, the electrode assembly comprising a plurality of individually addressable electrodes, each individually addressable electrode comprising one or more antennas, wherein the electrode assembly is configured to generate an electric field in a direction substantially parallel to the surface of the substrate support, and wherein the electrode assembly is integrated with the substrate support;
- a cavity positioned proximate to the surface of the substrate support; and
- at least one generator proximate to the cavity and configured to generate a standing wave within the cavity.

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