

Introducing Process Fluid Over Rotating Substrates

Background of the Invention

The invention relates to processing substrates.

Substrate processing systems are used to fabricate semiconductor logic and memory devices, flat panel displays, CD ROMs, and other devices. During processing, such substrates may be subjected to chemical vapor deposition (CVD) and rapid thermal processes (RTP), such as rapid thermal annealing (RTA), rapid thermal cleaning (RTC), rapid thermal CVD (RTCVD), rapid thermal oxidation (RTO), and rapid thermal nitridation (RTN). RTP systems usually include a heating element formed from, for example, one or more lamps, which radiatively heat the substrate through a light-transmissive window. RTP systems may also include one or more other optical elements, such as an optically reflective surface for defining a highly reflective cavity with the backside of the substrate and one or more optical detectors for measuring the temperature of the substrate during processing. The substrate may be rotated to improve the temperature uniformity across the surface of the substrate. During processing, a process gas may be injected into the processing system to react with the surface of the substrate. Many processing protocols call for the surface of the substrate to be uniformly processed. For this reason, it is often important that the substrate surface be heated uniformly and exposed uniformly to the process gas.

Summary of the Invention

In one aspect, the invention features an apparatus and methods for processing a substrate. In accordance with this inventive substrate processing scheme a substrate is rotated about a rotation axis in a processing chamber, a process fluid is introduced into the processing chamber, and one or more characteristic parameters of the process fluid are selectively controlled along a direction that is substantially perpendicular to a plane that is normal to the rotation axis.

In another aspect, the invention features a substrate processing apparatus having fluid delivery system that includes a first fluid injector constructed and arranged to

introduce a process fluid into the processing chamber from a first position and a second fluid injector constructed and arranged to introduce a process fluid into the processing chamber from a second position spaced from the first position along a direction that is substantially perpendicular to a plane that is normal to the rotation axis.

In yet another aspect, the invention features a substrate processing apparatus having a fluid delivery system that includes a first fluid injector constructed and arranged to introduce a process fluid into the processing chamber from a first position and a second fluid injector constructed and arranged to introduce a process fluid into the processing chamber from a second position spaced from the first position along a direction that is substantially perpendicular to a plane that is normal to the rotation axis. The first and second fluid injectors have respective outputs characterized by respective length dimensions along respective lines that are parallel to the plane that is normal to the rotation axis. The length dimension of the second fluid injector is greater than the length dimension of the first fluid injector.

In another aspect, the invention features a substrate processing apparatus having a fluid delivery system that includes a first fluid injector constructed and arranged to introduce a process fluid into the processing chamber from a first position and a second fluid injector constructed and arranged to introduce a process fluid into the processing chamber from a second position spaced from the first position along a direction that is substantially perpendicular to a plane that is normal to the rotation axis. The first and second fluid injectors have respective outputs characterized by respective width dimensions along respective lines that are perpendicular to the plane that is normal to the rotation axis. The width dimension of the second fluid injector is greater than the width dimension of the first fluid injector.

Embodiments may include one or more of the following features.

Process fluid may be introduced into the processing chamber by a fluid delivery system comprising a plurality of fluid injectors. The fluid delivery system may include: a first fluid injector constructed and arranged to introduce process fluid into the processing chamber and positioned a first distance above a reference plane

substantially containing the substrate surface; and a second fluid injector constructed and arranged to introduce process fluid into the processing chamber and spaced above the reference plane by a second distance which is greater than the first distance. The first fluid injector may be constructed and arranged to introduce fluid into the processing chamber from a first position, and the second fluid injector may be constructed and arranged to introduce fluid into the processing chamber from a second position spaced from the first position along a direction that is substantially perpendicular to a plane that is normal to the rotation axis. One or more of the fluid injectors may comprise a fluid port that has an elongated dimension. One or more of the fluid injectors may comprise a slot-shaped fluid port. The first fluid injector may have a first fluid port with a characteristic flow area and the second fluid injector has a second fluid port with a different characteristic flow area. The characteristic flow area of the second fluid port may be greater than the characteristic flow area of the first fluid port.

The processing apparatus may include a third fluid injector constructed and arranged to introduce fluid into the processing chamber and spaced above the reference plane by a third distance which is greater than the second distance. The first fluid injector, the second fluid injector, and the third fluid injector may be spaced apart along a direction that is substantially perpendicular to a plane that is normal to the rotation axis. The first fluid injector, the second fluid injector, and the third fluid injector may have respective fluid ports each with a different characteristic flow area.

A first process fluid may be introduced into the processing chamber from a position spaced a first distance above a reference plane substantially containing the substrate surface, and a second process fluid may be introduced into the processing chamber from a position spaced above the reference plane by a second distance which is greater than the first distance. The second process fluid may be introduced into the processing chamber from a position that is spaced apart from the position from which the first process fluid is introduced into the processing chamber along a direction that is substantially perpendicular to a plane that is normal to the rotation axis. The first process fluid may have substantially the same composition as the second process fluid.

The first process fluid may have a different composition than the second process fluid. The first process fluid may comprise a concentration of reactive species and the second process fluid may comprise a greater concentration of the same reactive species. The first process fluid may comprise a diluent. The second process fluid may comprise a reactive species and the first process fluid may be substantially free of any reactive species. The second process fluid may be introduced at a flow rate that is between about 0.01 times and about 100 times the speed at which a peripheral region of the substrate travels about a circular arc as the substrate rotates. The substrate may be rotated at a rate of about 50 rpm to about 240 rpm. The first process fluid and the second process fluid may be introduced into the processing chamber at flow speeds between about 0.15 m/s and about 15 m/s and, more preferably, between about 0.4 m/s and about 8 m/s.

Among the advantages of the invention are the following. The temperature across the substrate surface is maintained with a high uniformity as a result of rotation of the substrate. The substrate surface can be processed uniformly as a result of selective control over one or more characteristic parameters (e.g., injection velocity, volumetric flow rate, and composition) of the process fluid along a direction that is substantially perpendicular to a plane that is normal to the rotation axis. In one aspect, the surface of the substrate is uniformly exposed to process fluid as result of the rotation-induced reorientation of the vertical stack of process fluid, whereby process fluid is distributed uniformly across the substrate surface.

Other features and advantages will become apparent from the following description and from the claims.

Brief Description of the Drawings

Fig. 1 is a diagrammatic cross-sectional side view of a substrate processing system.

Fig. 2 is a diagrammatic view of a process gas flowing over the surface of a substrate.

Fig. 3 is a diagrammatic view of a process gas being injected from three fluid

injectors into a processing chamber containing a rotating substrate.

Fig. 4A is a diagrammatic top view of flow streamlines for a process gas introduced into a processing chamber from a fluid injector positioned at different distances above a substrate surface.

Fig. 4B is a diagrammatic side view of flow streamlines for a process gas introduced into a processing chamber from fluid injectors that are positioned at different horizontal locations at the same distance above a substrate surface.

Fig. 5A is a diagrammatic view of a fluid delivery system.

Fig. 5B is a cross-sectional side view of a block diffuser for the fluid delivery system of Fig. 5A along the line 5B-5B.

Fig. 5C is a diagrammatic front view of the block diffuser defining fluid injectors for the fluid delivery system of Fig. 5A.

Figs. 6A-6C are diagrammatic front views of face plates defining different fluid injectors.

Fig. 7 is a graph of film thickness plotted as a function of radial position across a substrate surface for two films grown as a result of exposure to a gas introduced into a processing chamber using the fluid injectors of Fig. 6C.

Description of the Preferred Embodiments

Referring to Fig. 1, a system 10 for processing a substrate 12 may include a processing chamber 14 that is radiatively heated through a water-cooled quartz window 18 by a heating lamp assembly 16. The peripheral edge of substrate 12 is supported by a rotatable support structure 20, which can rotate at a rate of up to about 120 rpm (revolutions per minute); support structure 20 preferably rotates at a rate of about 50-120 rpm, and more preferably at a rate of about 90 rpm. Beneath substrate 12 is a reflector plate assembly 22 that has an optically reflective surface facing the backside of substrate 12 to enhance the effective emissivity of substrate 12. Reflector plate assembly may be formed from nickel-plated aluminum. In a system designed for processing eight inch (200 mm) silicon wafers, reflector plate assembly 22 has a diameter of about 8.9 inches, the separation between substrate 12 and the top surface of reflector plate assembly 22 is about 5-10 mm, and the separation between substrate 12 and quartz window 18 is about

25 mm. In a system designed for processing twelve-inch (300 mm) silicon wafers, reflector plate assembly 22 has a diameter of about 13 inches, the separation between substrate 12 and the top surface of reflector plate assembly 22 is about 18 mm, and the separation between substrate 12 and quartz window 18 is about 30 mm. Reflector plate assembly 22 is mounted on a water-cooled base 23, which is typically maintained at a temperature of about 23° C. Substrate 12 is loaded into processing chamber through a port 21 (Fig. 3).

The temperatures at localized regions of substrate 12 are measured by a plurality of temperature probes 24 which are positioned to measure substrate temperature at different radial locations across the substrate. Temperature probes 24 receive light from inside the processing chamber through optical ports 25, 26, and 27, which extend through the top surface of reflector plate assembly 22 (processing system 10 may have a total of ten temperature probes; only three probes are shown in Fig. 1). At the reflector plate surface, each optical port may have a diameter of about 0.08 inch. Sapphire light pipes 29 are connected to optical fibers 31 for delivering the light received by the optical ports to respective optical detectors (for example, pyrometers), which are used to determine the temperature at the localized regions of substrate 12. Temperature measurements from the optical detectors are received by a controller 28 that controls the radiative output of heating lamp assembly 16; the resulting feedback loop improves the ability of the processing system to uniformly heat substrate 12.

In operation, a fluid delivery system 30 introduces a process gas into processing chamber 14 and directs the process gas toward a rotating substrate 12. The process gas flows across the top surface of substrate 12 and reacts with the heated substrate to form, for example, an epitaxial silicon film. Excess process gas, as well as any reaction by-products (such as hydrogen chloride given off by the reaction with the substrate), are withdrawn by a pump system 34 from processing chamber 14 through an exhaust port 32.

As shown in Fig. 2, during processing a process gas 36 that includes a reactive species 38 (e.g., trichlorosilane or dichlorosilane) flows over the surface of substrate 12 and must diffuse through a boundary layer 42 before contacting the substrate

surface to form a film 40 (e.g., epitaxial silicon). After reactive species 38 reacts with the substrate surface, reaction by-products 44 are typically produced. Reaction by-products 44 are swept away by the flow of process gas 36 toward exhaust 32. The rate at which film 40 grows on the substrate surface depends upon, among other factors, the thickness of the boundary layer through which reactive species 38 must diffuse and the temperature of the substrate at the reaction site. In a reaction rate limited regime, the uniformity of film growth is largely controlled by the temperature uniformity across the surface of the substrate. In a transport limited regime, the uniformity of film growth is largely controlled by the uniformity of process gas flow across the substrate surface, including the uniformity of the boundary layer formed over the substrate surface. As described in detail below, substantially uniform film growth has been achieved in a transport limited regime by controlling the vertical distribution of process gas introduced into the processing chamber above the surface of the substrate.

Referring to Fig. 3, in one embodiment, the vertical distribution of process gas introduced into processing chamber 14 is controlled by selecting characteristic parameters (e.g., injection velocity, composition, and volumetric flow rate) of the process gas respectively introduced by a fluid delivery system having three slot-shaped fluid injectors 46, 48, 50, which are spaced apart along a direction that is parallel to the axis about which the substrate rotates. Each fluid injector 46, 48, 50 introduces process gas into processing chamber 14 along respective flow paths 52, 54, 56 that are (at least initially) at different distances above the surface of substrate 12. As used herein, the distance above the substrate surface at which process gas is introduced into processing chamber 14 refers to the distance from the centroid of the surface defining the end of the fluid port to a plane that substantially contains the surface of the substrate. The fluid dynamics created by the rotation of substrate 12, reorients the vertical stack of process gas flows 52, 54, 56 and distributes the process gas flows to different horizontal locations over the surface of substrate 12. This horizontal redistribution of process gas can be exploited to control the supply of reactive species across the substrate 12.

The fluid delivery system in the embodiment of Fig. 3 has three fluid injectors. In general, the fluid delivery system can have at least two fluid injectors located at different heights above the substrate surface; one or more other fluid injectors may be included at the same or different heights above the substrate to achieve different processing effects.

Fig. 4A illustrates the results of a computer simulation of process gas flow streamlines introduced from four fluid injectors positioned at different distances above the substrate surface (1.0 mm, 1.5 mm, 2.0 mm, and 6.0 mm). This simulation was based upon a flow of trichlorosilane in hydrogen at 40 slm (standard liters per minute) introduced through a fluid injector with a flow area of 0.15 square inches, and a substrate rotation rate of 85 rpm. Assuming the substrate rotates counterclockwise when viewed from above, the shorter the distance is between the location at which process fluid is introduced into processing chamber 14 and the substrate surface, the more the process gas flow streamlines are displaced to the peripheral edge of the rotating substrate. Process gas introduced at a distance of 1.0 mm above the substrate surface supplies process gas primarily to the peripheral edge of the substrate, whereas process gas introduced at a distance of 6.0 mm above the substrate surface supplies process gas primarily to the central region of the substrate. Process gas introduced at intermediate locations above the substrate surface (1.5 mm and 2.0 mm) supply process gas primarily to regions between the peripheral edge and the center of the substrate. Thus, the distribution of process gas across the substrate surface can be controlled by varying characteristic parameters of the process gas introduced into processing chamber 14 at different distances above the substrate surface.

Fig. 4B illustrates the results of another computer simulation in which process gas is introduced into processing chamber 14 from six fluid injectors 58-63 horizontally spaced apart and located at the same distance above the substrate surface. This simulation was based upon a flow of trichlorosilane in hydrogen at 40 slm (standard liters per minute) introduced through a fluid injector with a flow area of 0.15 square inches and located a distance of 14 mm above the substrate surface, and a

substrate rotation rate of 85 rpm. Assuming the substrate rotates counterclockwise when viewed from above, the process gas introduced from fluid injector 58 is deflected to the peripheral edge of the substrate. The process gas introduced from the other fluid injectors 59-63 is deflected over the process gas flow from fluid injector 58 to a substantial distance above the substrate surface and contributes little to the reaction with the substrate surface relative to the contribution from the process gas introduced from fluid injector 58. In other words, in this arrangement, the reaction of process gas with the substrate surface is largely dominated by the flow dynamics of process gas introduced by fluid injector 58. The control over the distribution of process gas across the substrate surface is therefore significantly limited in this arrangement.

The rate at which process gas is introduced into processing chamber 14 is selected so that the process gas flow velocity at the peripheral edge of the substrate is roughly the same order of magnitude as the speed of the peripheral edge of the substrate as it rotates. For example, the process gas is introduced at a flow rate that is preferably between about 0.01 times and about 100 times and, more preferably, between about 0.1 times and about 10 times the speed at which a peripheral region of the substrate travels about a circular arc as the substrate rotates. Thus, for a 300 mm diameter substrate that rotates at a rate of about 50 rpm to about 240 rpm, the process gas is introduced at a flow speed of about 0.008-0.04 m/s to about 80-400 m/s, and more preferably at a flow speed of about 0.08-0.4 m/s to about 8-40 m/s; the process gas is preferably introduced at a flow rate of about 0.15 m/s to about 15 m/s for a 300 mm substrate rotating at about 90 rpm. The speed at which process gas is introduced into the processing chamber is measured at the output of the fluid injector, and may be determined from the process gas flow rate and the flow area of the fluid injector.

Referring to Figs. 5A-5C, fluid delivery system 30 includes a face plate 70 that defines the outputs of fluid injectors 46, 48, 50. Fluid delivery system 30 also includes a flange 74 that is attached to processing chamber 14 and a block diffuser 72, which receives the process gas from a gas supply and produces a uniform process gas flow. Process gas is respectively delivered to fluid injectors 46, 48, 50 through fluid

inputs 76, 78, 80. Each fluid injector includes a plenum which receives process gas from one of fluid inputs 76, 78, 80. As shown in Fig. 5B, process gas flows from fluid input 80, through a plurality of orifices 82, into a plenum 84, and finally through the output of fluid injector 50. Face plate 70 has through-holes 86, 88 (Fig. 5C) and diffuser 72 has through-holes 90, 92 for receiving bolts which secure face plate 70 and diffuser 72 to flange 74. In a processing chamber designed for growing epitaxial silicon on 300 mm diameter silicon substrates, orifices 82 have a diameter "d" of about 0.062 inch; and the outputs of fluid injectors 46, 48, 50 have an elongated dimension "t" of about 1.467 inches, a width "w" of about 0.17 inch, and are spaced apart by a distance "s" of about 0.05 inch. In another embodiment designed for growing epitaxial silicon on 300 mm diameter silicon substrates, orifices 82 have a diameter of about 0.062 inch and the outputs of fluid injectors 46, 48, 50 have an elongated dimension of about 1.25 inches, a width of about 0.14 inch, and are spaced apart by a distance of about 0.08 inch.

Referring to Figs. 6A and 6B, the fluid injectors can have outputs with different flow areas. This allows the volumetric flow rate at different distances above the substrate surface to be easily controlled. For example, as shown in Fig. 6A, the outputs of fluid injectors 100, 102, 104, which are defined in face plate 106, can have that same width dimension and different elongated (length) dimensions. In a processing chamber designed for growing epitaxial silicon on 300 mm diameter silicon substrates, the outputs of fluid injectors 100, 102, 104 have a width "w1" dimension of about 0.07 inch and respective length dimensions "t1", "t2", and "t3" of about 0.5 inch, about 0.9 inch, and about 1.25 inches. The outputs are spaced apart by a distance "s1" of about 0.15 inch. In contrast, as shown in Fig. 6B, the outputs of fluid injectors 110, 112, 114, which are defined in face plate 116 can have that same length dimension and different width dimensions. In a processing chamber designed for growing epitaxial silicon on 300 mm diameter silicon substrates, the outputs of fluid injectors 110, 112, 114 have a length dimension "t4" of about 1.25 inch and respective width dimensions "w2", "w3", and "w4" of about 0.135 inch, about 0.09 inch, and about 0.045 inches. The outputs of fluid injectors 110 and 112 are spaced apart by a

distance "s2" of about 0.11 inch, and the outputs of fluid injectors 112 and 114 are spaced apart by a distance "s3" of about 0.15 inch.

Referring to Fig. 6C, in another embodiment, fluid injectors 120 and 122 are arranged to introduce process fluid into processing chamber 14 along flow paths that are at different distances above the surface of substrate 12. Fluid injectors 120 and 122 are spaced apart along a direction that is substantially perpendicular to a plane that is normal to the axis about which the substrate is rotated. Fluid injectors 124, 126, 128, and 130 are arranged to introduce process fluid at the same distance above the surface of substrate 12 as fluid injector 120.

In operation, characteristic parameters of the process gas can be controlled along a direction that is substantially parallel to the rotation axis. These parameters can be controlled in different ways to achieve a uniform distribution of process gas across the substrate surface. Process gas can be introduced through the different fluid injectors at different flow velocities or at different volumetric flow rates, or both.

The process gas introduced through different fluid injectors can also have different compositions. For example, a diluent gas (e.g., hydrogen, helium, and argon) can be added to the reactive gas species supplied to one or more of the fluid injectors and undiluted process gas can be supplied to the other fluid injectors to achieve a uniform growth rate across the substrate surface. In the embodiment of Fig. 6C, reactive process gas can be introduced through fluid injectors 120, 124, 126, 128 and 130, and an inert process gas can be introduced through fluid injector 122. This fluid introduction scheme has been found to compensate for the experimentally observed increased film growth rate at the peripheral edge of the wafer when process gas is introduced from a horizontal array of fluid injectors positioned at the same distance above the surface of the substrate.

Referring to Fig. 7, the solid line represents the film growth uniformity that results when the same reactive gas species (trichlorosilane in a hydrogen carrier) is introduced from fluid injectors 120, 124, 126, 128 and 130, with no process gas flowing through fluid injector 122. The dashed line represents the improved film growth uniformity that results when the same reactive process gas (trichlorosilane in a

hydrogen carrier) is introduced into processing chamber 14 from fluid injectors 120, 124, 126, 128, and 130, and an inert process gas (hydrogen) is introduced into processing chamber 14 from fluid injector 122. Based on the flow streamlines shown in Fig. 4A, it is believed that the hydrogen gas flow is deflected to the peripheral edge of the substrate and thereby dilutes the reactive gas concentration to slow down the film growth rate at the peripheral edge.

Thus, the inventive apparatus and methods described herein provide selective control over one or more characteristic parameters (e.g., injection velocity, volumetric flow rate, and composition) of the process fluid along a direction that is substantially perpendicular to a plane that is normal to the axis about which the substrate is rotated. In one aspect, the surface of the substrate is uniformly exposed to process fluid as result of a rotation-induced reorientation of the vertical stack of process fluid, whereby process fluid is distributed uniformly across the substrate surface.

Other embodiments are within the scope of the claims.



What is claimed is:

1. An apparatus for processing a substrate, comprising:
a processing chamber;
a rotatable substrate support located within the processing chamber and constructed to rotate the substrate about a rotation axis; and
a fluid delivery system constructed and arranged to introduce a process fluid into the processing chamber and to enable selective control over one or more characteristic parameters of the process fluid along a direction that is substantially perpendicular to a plane that is normal to the rotation axis.
2. The apparatus of claim 1 wherein the fluid delivery system comprises a plurality of fluid injectors for introducing process fluid into the processing chamber.
3. The apparatus of claim 1 wherein the fluid delivery system comprises:
a first fluid injector constructed and arranged to introduce a process fluid into the processing chamber and positioned a first distance above a reference plane substantially containing the substrate surface; and
a second fluid injector constructed and arranged to introduce process fluid into the processing chamber and positioned above the reference plane a second distance which is greater than the first distance.
4. The apparatus of claim 3 wherein the first fluid injector is constructed and arranged to introduce fluid into the processing chamber from a first position, and the second fluid injector is constructed and arranged to introduce fluid into the processing chamber from a second position spaced from the first position along a direction that is substantially perpendicular to a plane that is normal to the rotation axis.
5. The apparatus of claim 2 wherein one or more of the fluid injectors



comprises a fluid port that has an elongated dimension.

6. The apparatus of claim 3 wherein one or more of the fluid injectors comprises a slot-shaped fluid port.

7. The apparatus of claim 3 wherein the first fluid injector has a first fluid port with a characteristic flow area and the second fluid injector has a second fluid port with a different characteristic flow area.

8. The apparatus of claim 7 wherein the characteristic flow area of the second fluid port is greater than the characteristic flow area of the first fluid port.

9. The apparatus of claim 3 further comprising a third fluid injector constructed and arranged to introduce fluid into the processing chamber and positioned above the reference plane a third distance which is greater than the second distance.

10. The apparatus of claim 9 wherein the first fluid injector, the second fluid injector, and the third fluid injector are spaced apart along a direction that is substantially perpendicular to a plane that is normal to the rotation axis.

11. The apparatus of claim 9 wherein the first fluid injector, the second fluid injector, and the third fluid injector have respective fluid ports each with a different characteristic flow area.

12. An apparatus for processing a substrate, comprising:
a processing chamber;
a rotatable substrate support located within the processing chamber and constructed to rotate the substrate about a rotation axis; and
a fluid delivery system having a first fluid injector constructed and arranged to



introduce a process fluid into the processing chamber from a first position and a second fluid injector constructed and arranged to introduce a process fluid into the processing chamber from a second position spaced from the first position along a direction that is substantially perpendicular to a plane that is normal to the rotation axis.

13. An apparatus for processing a substrate, comprising:

a processing chamber;

a rotatable substrate support located within the processing chamber and constructed to rotate the substrate about a rotation axis; and

a fluid delivery system having a first fluid injector constructed and arranged to introduce a process fluid into the processing chamber from a first position and a second fluid injector constructed and arranged to introduce a process fluid into the processing chamber from a second position spaced from the first position along a direction that is substantially perpendicular to a plane that is normal to the rotation axis; wherein the first and second fluid injectors have respective outputs characterized by respective length dimensions along respective lines that are parallel to the plane that is normal to the rotation axis, the length dimension of the second fluid injector being greater than the length dimension of the first fluid injector.

14. An apparatus for processing a substrate, comprising:

a processing chamber;

a rotatable substrate support located within the processing chamber and constructed to rotate the substrate about a rotation axis; and

a fluid delivery system having a first fluid injector constructed and arranged to introduce a process fluid into the processing chamber from a first position and a second fluid injector constructed and arranged to introduce a process fluid into the processing chamber from a second position spaced from the first position along a direction that is substantially perpendicular to a plane that is normal to the rotation axis; wherein the first and second fluid injectors have respective outputs characterized by respective



width dimensions along respective lines that are perpendicular to the plane that is normal to the rotation axis, the width dimension of the second fluid injector being greater than the width dimension of the first fluid injector.

15. An apparatus for processing a substrate, comprising:
a processing chamber;
a rotatable substrate support located within the processing chamber and constructed to rotate the substrate about a rotation axis; and
a fluid delivery system having a first fluid injector positioned a first distance above a reference plane substantially containing the substrate surface and a plurality of other fluid injectors each of which is positioned above the reference plane a second distance which is greater than the first distance.

16. A method of processing a substrate, comprising:
rotating a substrate inside a processing chamber about a rotation axis;
introducing a process fluid into the processing chamber; and
selectively controlling one or more characteristic parameters of the process fluid along a direction that is substantially perpendicular to a plane that is normal to the rotation axis.

17. The method of claim 15 wherein characteristic parameters of the process gas are selectively controlled by:

introducing a first process fluid into the processing chamber from a position spaced a first distance above a reference plane substantially containing the substrate surface; and

introducing a second process fluid into the processing chamber from a position spaced above the reference plane by a second distance which is greater than the first distance.

18. The method of claim 16 wherein the second process fluid is introduced



into the processing chamber from a position that is spaced apart from the position from which the first process fluid is introduced into the processing chamber along a direction that is substantially perpendicular to a plane that is normal to the rotation axis.

19. The method of claim 16 wherein the first process gas has substantially the same composition as the second process fluid.

20. The method of claim 16 wherein the first process gas has a different composition than the second process fluid.

21. The method of claim 16 wherein the first process fluid comprises a concentration of reactive species and the second process fluid comprises a greater concentration of the same reactive species.

22. The method of claim 20 wherein the first process fluid comprises a diluent.

23. The method of claim 16 wherein the second process fluid comprises a reactive species and the first process fluid is substantially free of any reactive species.

24. The method of claim 16 wherein the first process fluid and the second process fluid are introduced at flow rates that are between about 0.01 times and about 100 times the speed at which a peripheral region of the substrate travels about a circular arc as the substrate rotates.

25. The method of claim 16 wherein the substrate is rotated at a rate of about 50 rpm to about 240 rpm.

26. The method of claim 16 wherein the first process fluid and the second process fluid are introduced into the processing chamber at flow speeds between about



0.15 m/s and about 15 m/s.

27. The method of claim 16 wherein the first process fluid and the second process fluid are introduced into the processing chamber at flow speeds between about 0.4 m/s and about 8 m/s.