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(54) **PLASMA REACTOR WITH TILTABLE OVERHEAD RF INDUCTIVE SOURCE**

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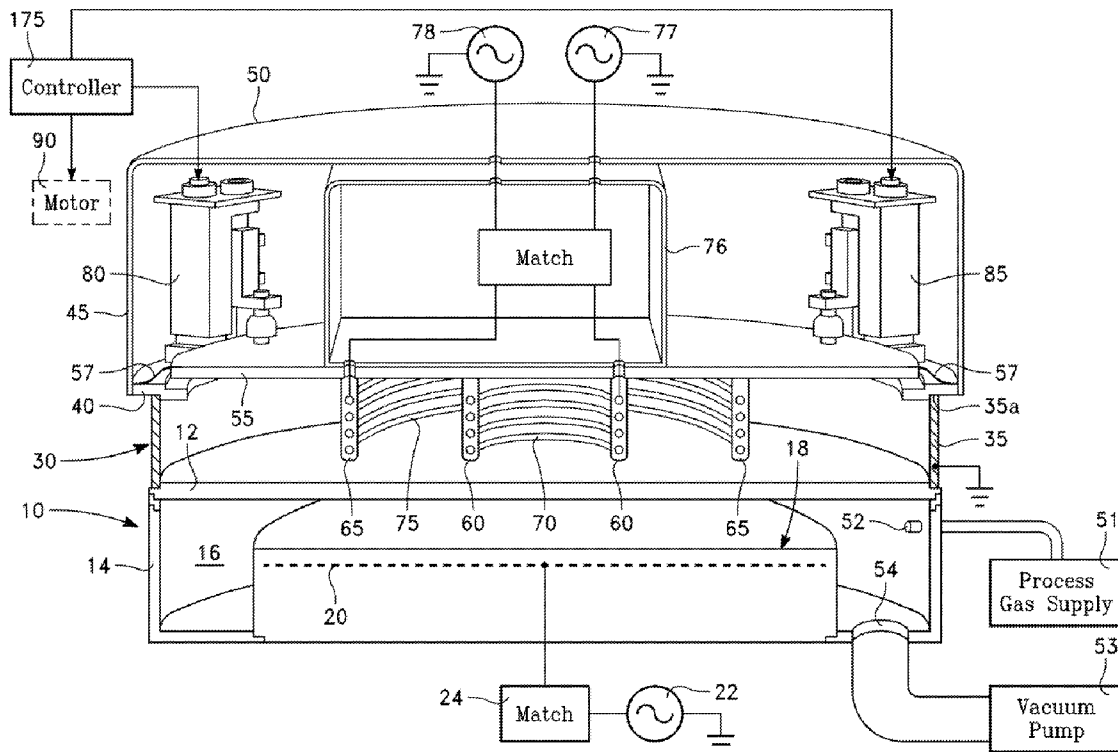
(57) **ABSTRACT**

Correction of skew in plasma etch rate distribution is performed by tilting the overhead RF source power applicator about a tilt axis whose angle is determined from skew in processing data. Complete freedom of movement is provided by incorporating exactly three axial motion servos supporting a floating plate from which the overhead RF source power applicator is suspended.

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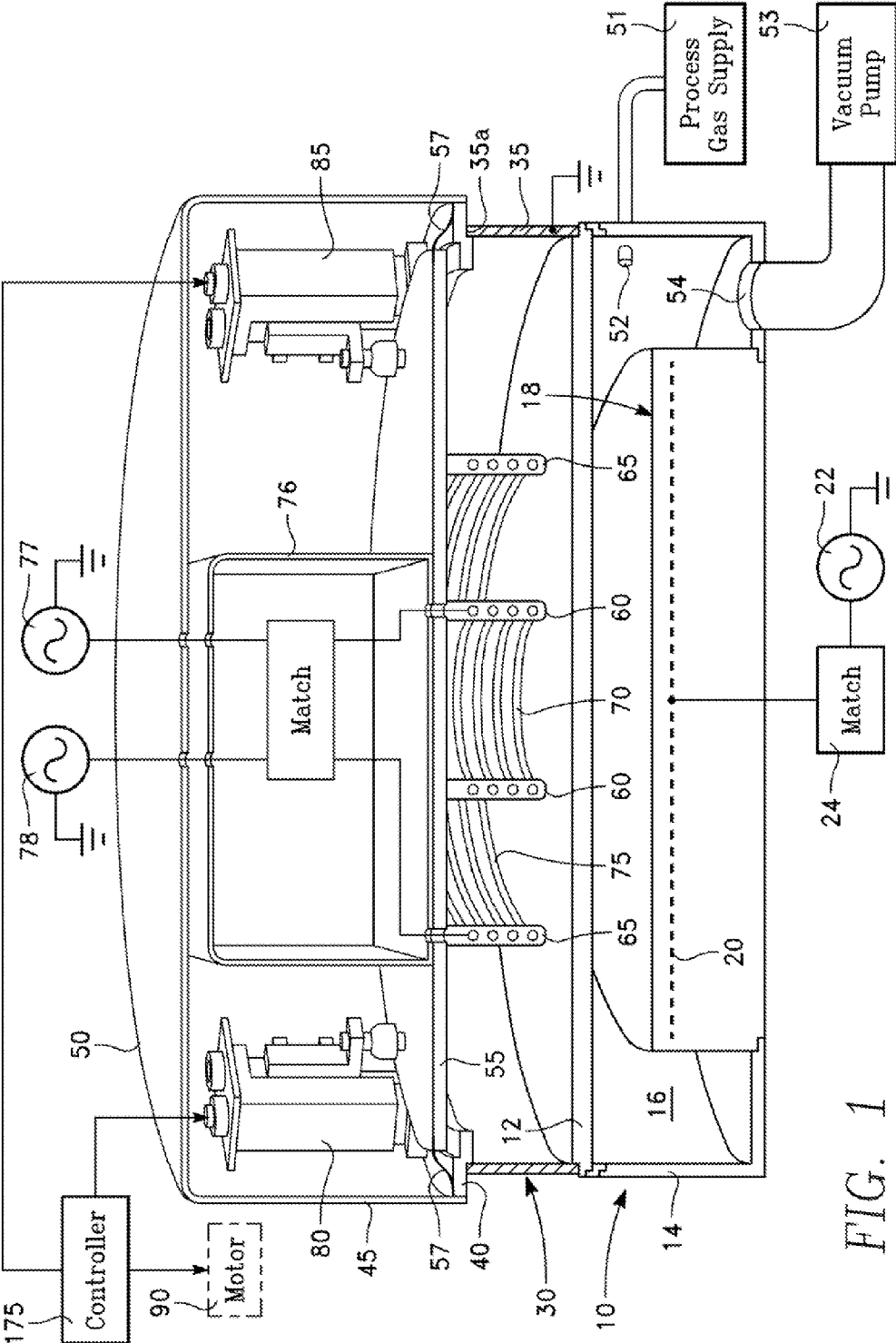


FIG. 1

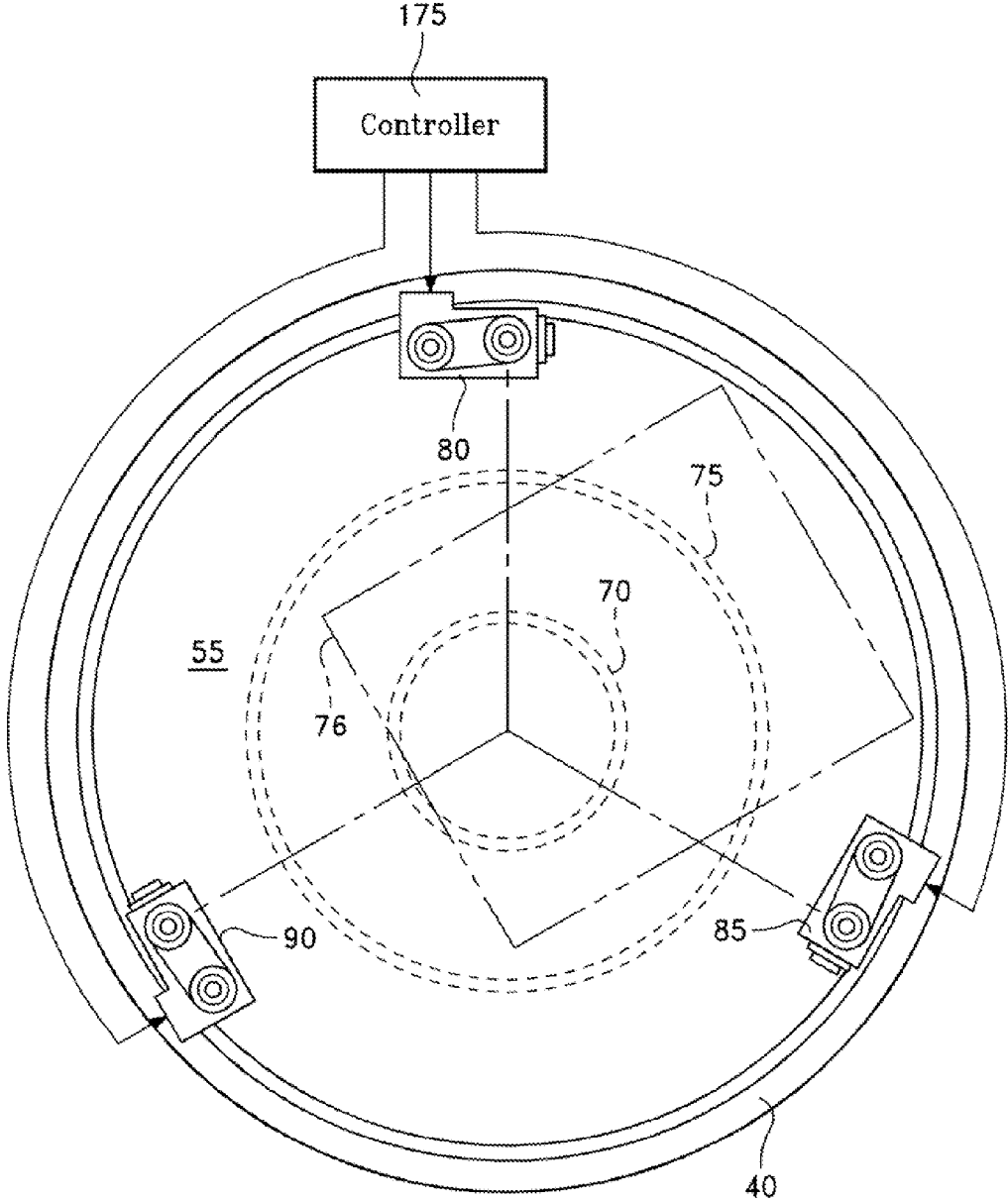


FIG. 2

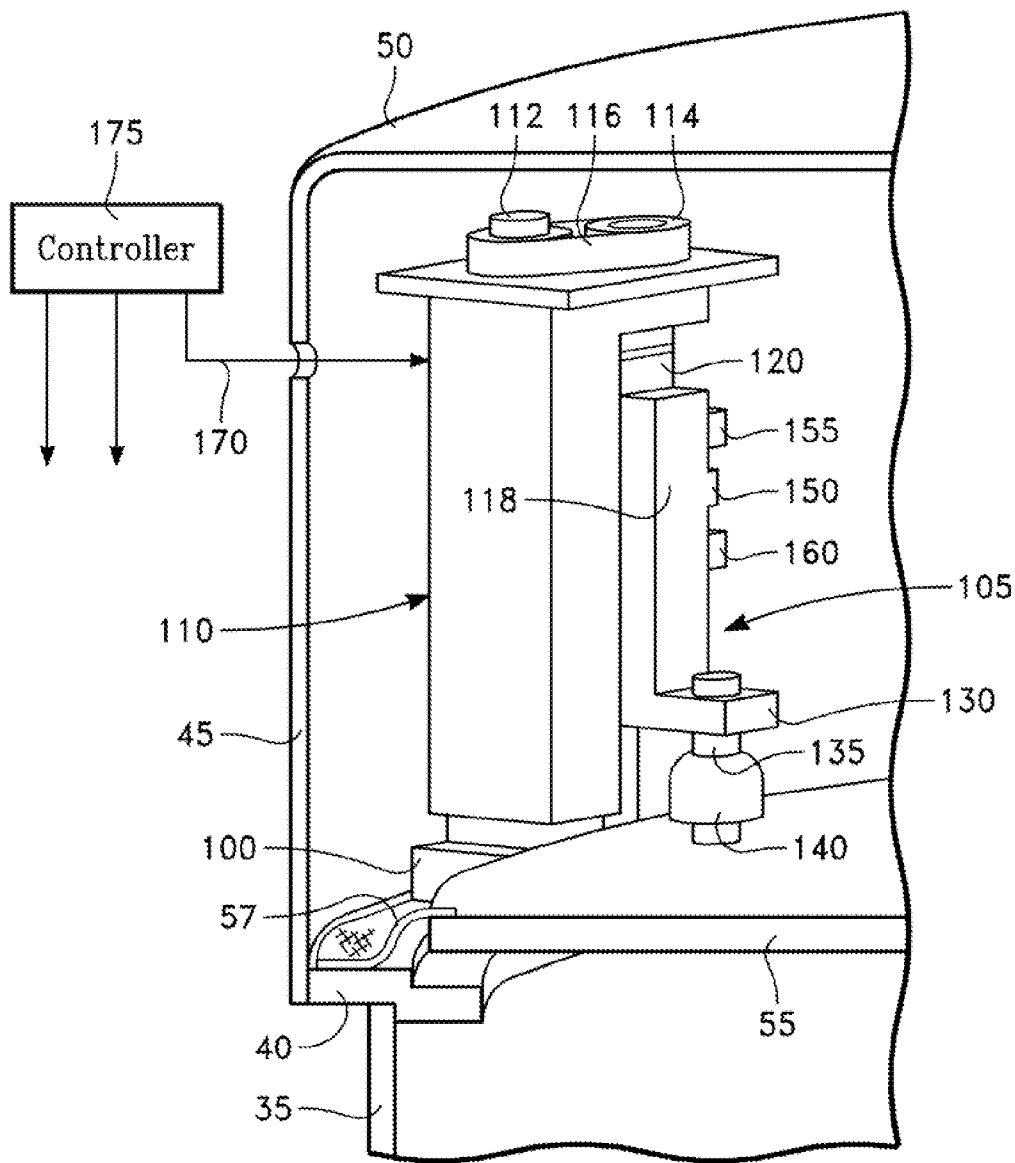


FIG. 3

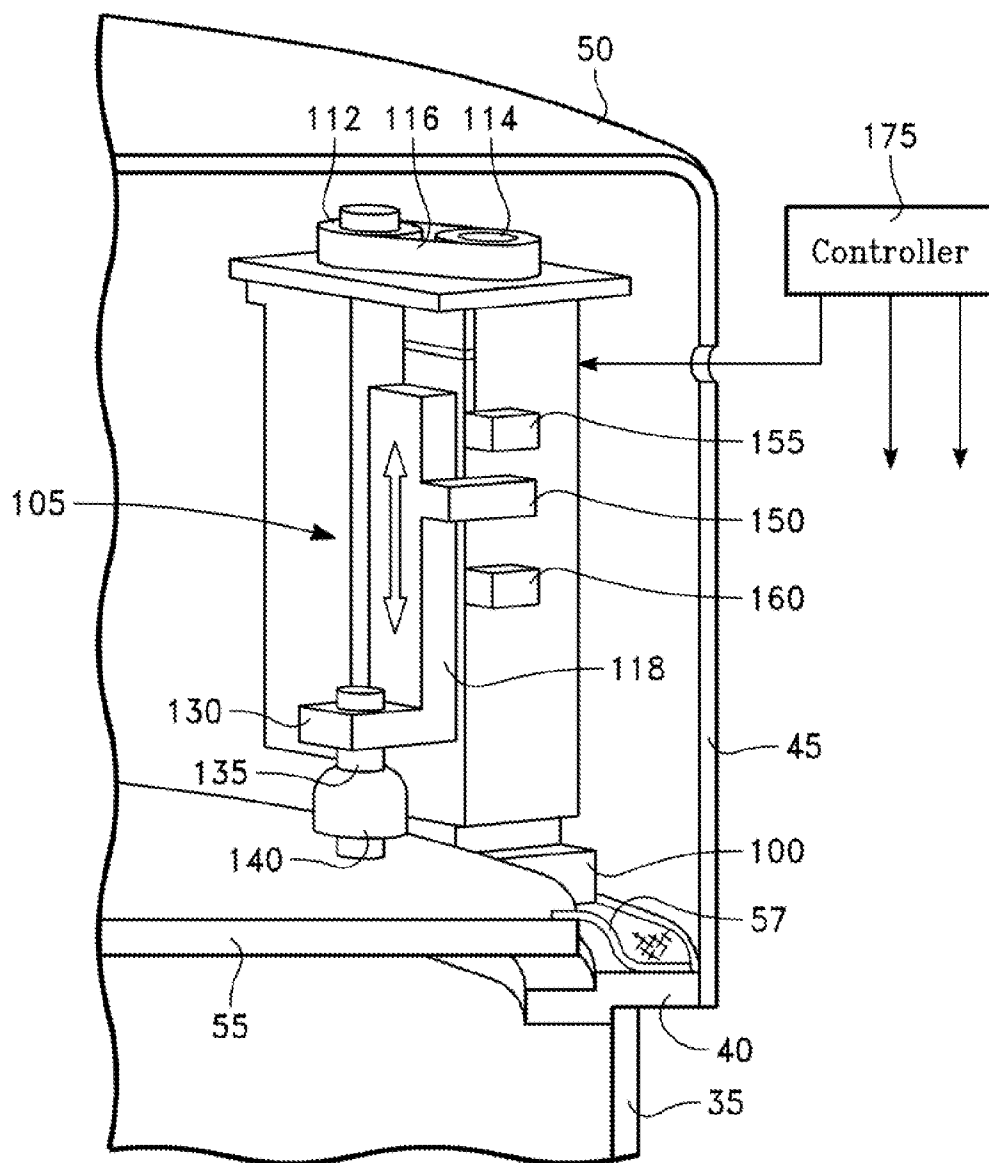


FIG. 4

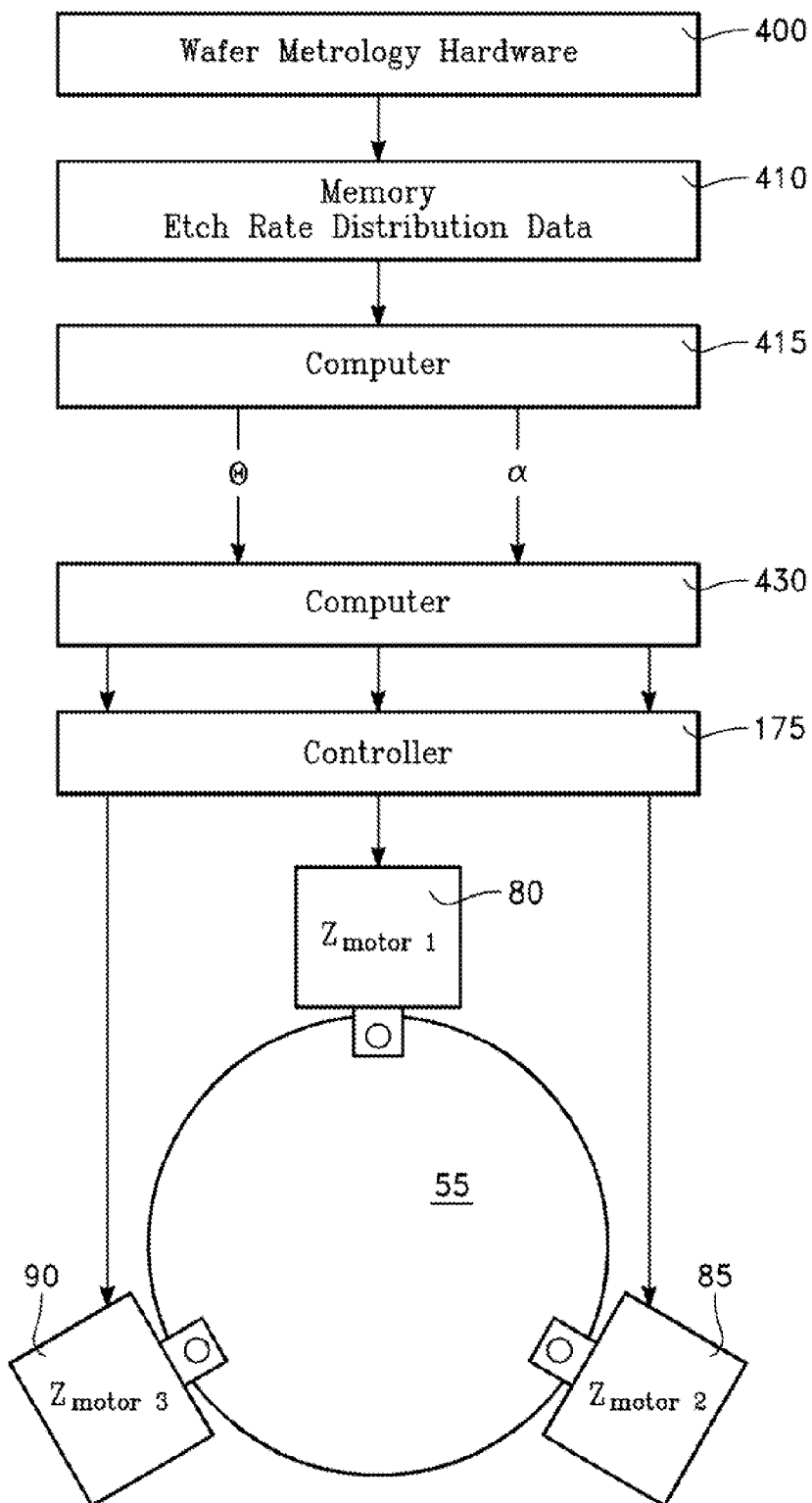


FIG. 5

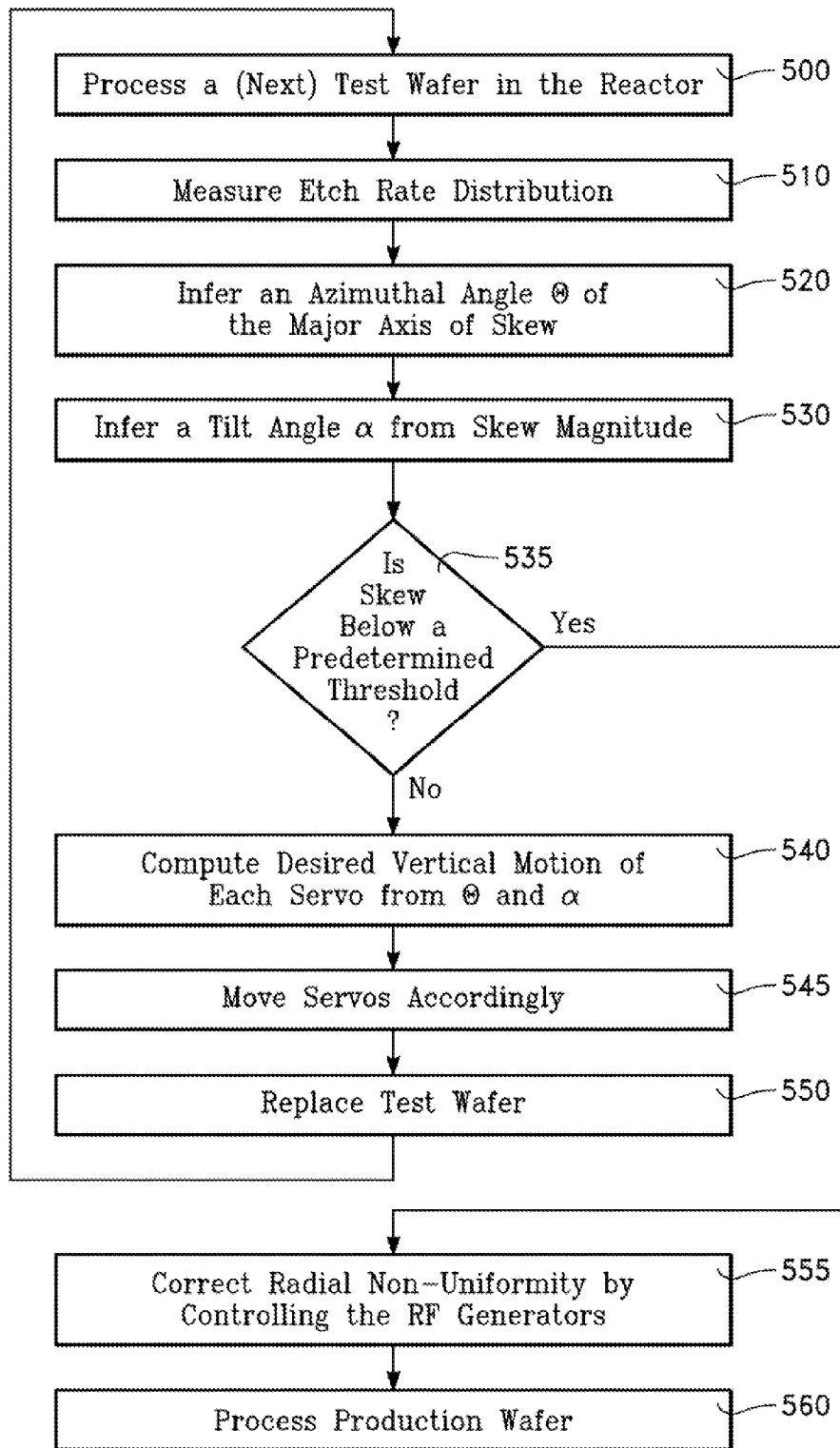


FIG. 6

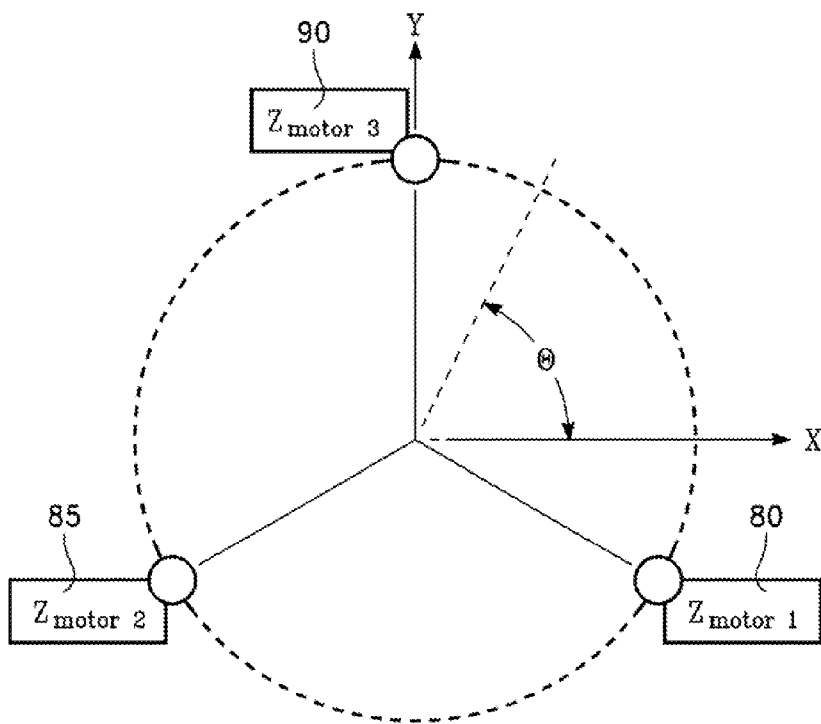


FIG. 7

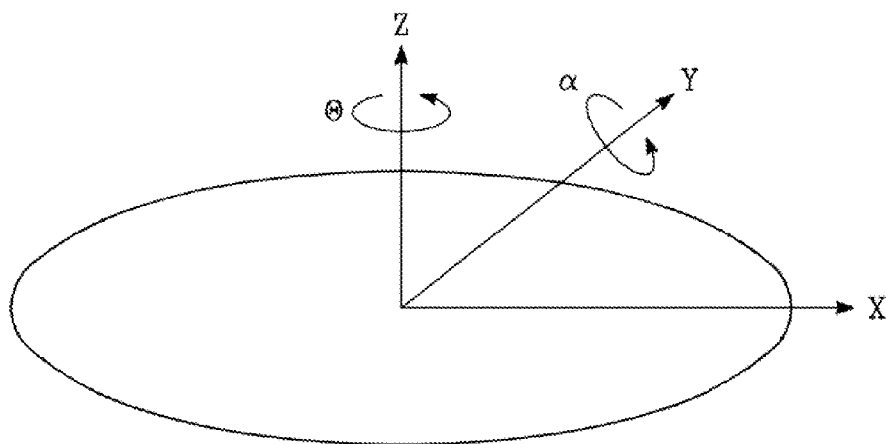
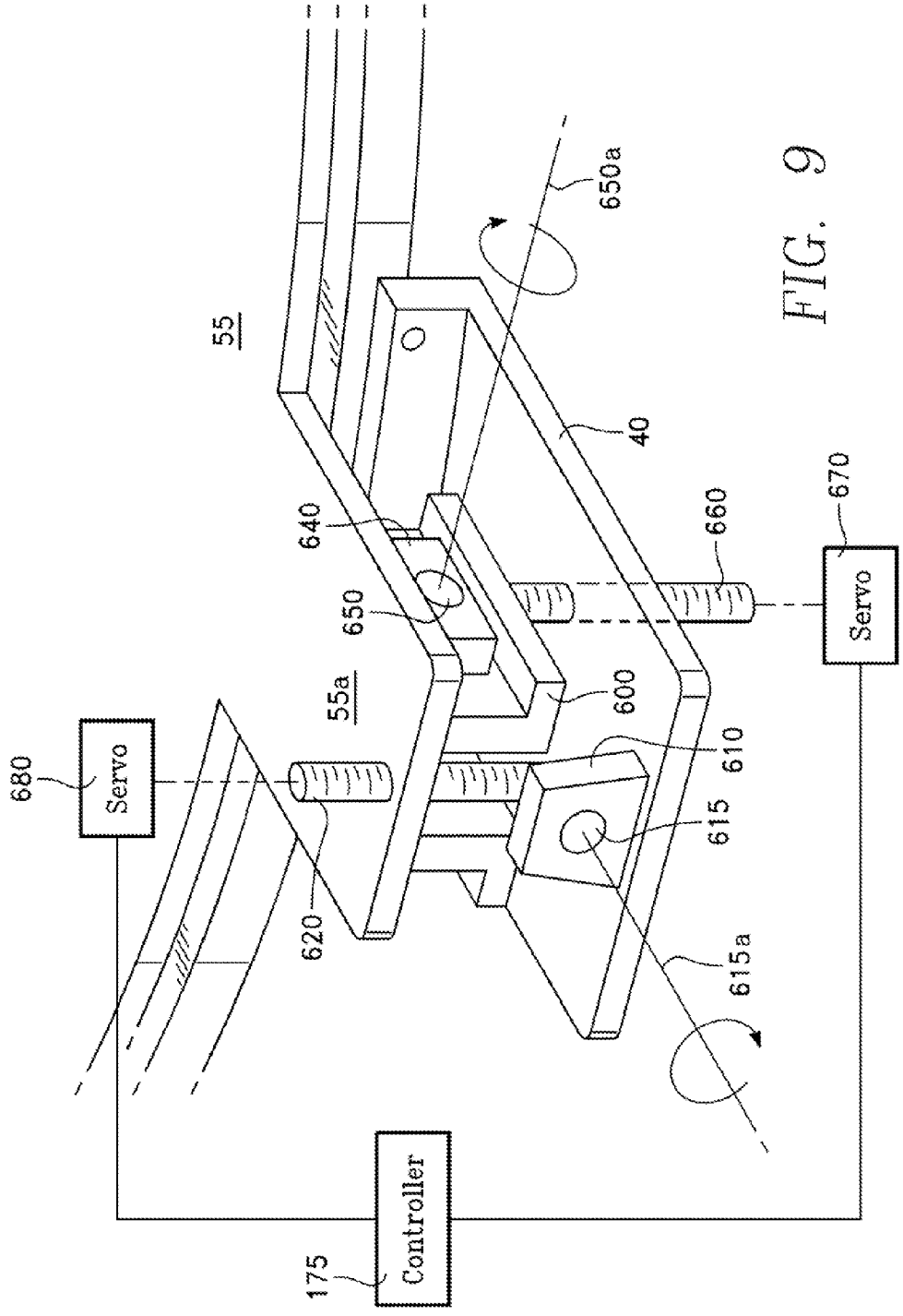


FIG. 8



PLASMA REACTOR WITH TILTABLE OVERHEAD RF INDUCTIVE SOURCE

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] This application claims the benefit of U.S. Provisional Application Ser. No. 61/239,711, filed Sep. 3, 2009 entitled PLASMA REACTOR WITH TILTABLE OVERHEAD RF INDUCTIVE SOURCE, by Kenneth Collins, et al.

BACKGROUND

[0002] Plasma etch processes are employed in microelectronic circuit fabrication to define thin film structures on semiconductor wafers or workpieces. Generally, a disc-shaped workpiece is processed in a cylindrical reactor chamber. Features sizes in the thin film structures formed by the etch process can be as small as tens of nanometers, for example. Uniformity of etch rate distribution across the entire surface of the workpiece is critical in attaining workable devices. The etch rate distribution reflects the plasma ion density distribution across the workpiece surface existing during the plasma etch processing of the workpiece. Etch processes can employ an inductively coupled RF plasma in which the plasma source consists of a coil antenna over the ceiling of the reactor chamber. The etch rate distribution can have a radial non-uniformity, in which the non-uniformity pattern is generally symmetrical about the cylindrical axis of symmetry of the reactor chamber. For example, the etch rate distribution may reflect a plasma ion density distribution that is, predominantly, either center-high or center low. Such a radial pattern of non-uniformity can be corrected by dividing the ceiling coil antenna into two or more concentric coil antennas that are separate from one another and are independently powered with RF power. Radial non-uniformity in etch is corrected in such a reactor by adjusting the RF power levels independently delivered to the separate concentric coil antennas. While this arrangement works well in correcting radial non-uniformities in etch rate distribution, it is not well-suited for correcting for asymmetrical non-uniformities in etch rate distribution. Such asymmetrical non-uniformities may be referred to as "skew" non-uniformities, and typically are manifested as a difference between etch rates on opposite sides of the workpiece. As one simplified example, one half of the workpiece may experience a higher etch rate than the other half. Under real production conditions, it is often found that the etch rate distribution measured across the surface of the workpiece has both radial non-uniformity and skew non-uniformity in combination. If the skew non-uniformity could be somehow corrected or eliminated, then the remaining non-uniformity, namely the radial non-uniformity, could be eliminated by apportioning the RF power levels delivered to the different concentric overhead coil antennas. The result would be correction of all etch rate distribution non-uniformity across the workpiece surface. The problem is how to eliminate the skew non-uniformity in etch rate distribution.

SUMMARY

[0003] A plasma reactor for processing a workpiece includes a processing chamber enclosure defining a process chamber interior and comprising a chamber side wall and a chamber ceiling, and a workpiece holder inside the process chamber interior and a conductive RF enclosure overlying the

ceiling and comprising an RF enclosure side wall and an RF enclosure top cover. A shoulder ring is supported on the RF enclosure side wall, and a floating support plate is placed inside the conductive RF enclosure and adjacent the shoulder ring. Plural radially inner and outer RF plasma source power applicators are suspended from the floating support plate in a space below the floating support plate and above the chamber ceiling. Plural RF power sources are coupled to a corresponding one of the plural RF plasma power applicators. Plural actuators fixed with respect to the shoulder ring are spaced about the shoulder ring at periodic intervals. Each one of the plural actuators has an axially movable arm and a motor driving the movable arm in an axial direction. A rotatable joint having two joint ends is provided, one of the joint ends being connected to the axially movable arm and the other of the joint ends being connected to a portion of the floating support plate adjacent the one actuator, whereby the floating plate is supported at respective plural locations by the rotatable joint of each respective one of the plural actuators. Only three actuators are provided in the preferred embodiment, to ensure complete freedom of movement of the floating support plate.

BRIEF DESCRIPTION OF THE DRAWINGS

[0004] So that the manner in which the exemplary embodiments of the present invention are attained and can be understood in detail, a more particular description of the invention, briefly summarized above, may be had by reference to the embodiments thereof which are illustrated in the appended drawings. It is to be appreciated that certain well known processes are not discussed herein in order to not obscure the invention.

[0005] FIG. 1 is a partially cut-away side view of a reactor in accordance with an embodiment.

[0006] FIG. 2 is a top view corresponding to FIG. 1.

[0007] FIG. 3 is an enlarged view of a portion of the reactor of FIG. 1.

[0008] FIG. 4 is another enlarged view corresponding to FIG. 3.

[0009] FIG. 5 is a block diagram of a control system included in the reactor of FIG. 1.

[0010] FIG. 6 is a block flow diagram depicting operation of the control system of FIG. 5.

[0011] FIG. 7 depicts a coordinate system employed in the control system of FIG. 5 to control the motion of the overhead coil source of FIG. 1 in accordance with an embodiment.

[0012] FIG. 8 is a diagram depicting the three-dimensional locations of the actuators of the reactor of FIG. 1 in one implementation.

[0013] FIG. 9 depicts a reactor in accordance with alternative embodiment.

[0014] To facilitate understanding, identical reference numerals have been used, where possible, to designate identical elements that are common to the figures. It is contemplated that elements and features of one embodiment may be beneficially incorporated in other embodiments without further recitation. It is to be noted, however, that the appended drawings illustrate only exemplary embodiments of this invention and are therefore not to be considered limiting of its scope, for the invention may admit to other equally effective embodiments.

DETAILED DESCRIPTION

[0015] Referring FIGS. 1-4 depict a reactor of the type employed to carry out a reactive ion etch process using an RF

inductively coupled plasma. The reactor includes a chamber enclosure 10 including a disk-shaped ceiling 12 and a cylindrical side wall 14 defining a chamber 16. Inside the chamber 16 is a workpiece support pedestal 18 including a bias electrode 20. A plasma bias power generator 22 is coupled through an RF bias impedance match 24 to the bias electrode 20.

[0016] An RF enclosure 30 formed of metal is provided above the ceiling 12 and includes a metallic grounded base cylindrical side wall 35 having a top edge 35a supporting a shoulder ring 40, and a conductive top cylindrical side wall 45 extending from the shoulder ring 40 and supporting an overlying conductive cover 50. The cover 50 and the top cylindrical side wall 45 may be integrally formed together and may be coupled to RF ground.

[0017] A process gas supply 51 provides process gas into the chamber 16 through process gas distribution apparatus 52 which may be provided in the side wall 14 (as shown) or in the ceiling 12, for example. A vacuum pump 53 evacuates the chamber 16 through a pumping port 54.

[0018] A floating support plate 55 is located on or slightly above the shoulder ring 40, and is supported in a manner to be described below. An inductively coupled plasma source power applicator is supported below the support plate 55 by two sets of brackets 60, 65 extending downwardly from the support plate 55. The plasma source power applicator includes a helical inner coil antenna 70 supported and a helical outer coil antenna 75 concentric with the inner coil antenna 70. The set of brackets 60 support the inner coil antenna 70 while the set of brackets 65 support the outer coil antenna 75. An RF impedance match box 76 rests on the support plate 55. A first RF power generator 77 is coupled to the inner coil antenna 70 through impedance match elements (not shown) in the impedance match box 76. A second RF power generator 78 is coupled to the outer coil antenna 75 through other impedance match elements (not shown) in the impedance match box 76.

[0019] A flexible RF gasket 57 provides an RF shield and electrical continuity between the shoulder ring 40 and the floating support plate 55. The RF gasket 57 may be an annular copper mesh, and may be interrupted to accommodate three support servos described below.

[0020] The support plate 55 is supported by three support servos 80, 85, 90 placed at equal (120 degree) intervals on the shoulder ring 40. The support servos 80, 85, 90 are identical in one embodiment, and each consists of a support base 100 fastened to a top surface of the shoulder ring 40, a rail and runner block 105 and a servo motor 110. In the illustrated embodiment, the rail and runner block 105 is fastened to the support base 100 while the servo motor 110 is fastened to the rail and runner block 105, although this relationship may be modified or reversed in other embodiments. The servo motor 110 rotates a drive pulley 112 and the rail and runner block 105 has a driven pulley 114, the pulleys 112, 114 being linked by a drive belt 116. The rail and runner block 105 has a vertically actuated elevator block 118 constrained by a linear vertical internal rail 120 within the rail and runner block 105, the elevator block 118 being lifted or depressed along the vertical rail 120 depending upon whether the driven pulley 114 is rotated clockwise or counter clockwise. The elevator block includes a radial arm 130 that extends over the floating support plate 55. A vertical strut 135 supported by the radial arm 130 extends downwardly toward the support plate 55. A conventional rotatable ball joint 140 is coupled between the

strut 135 and the support plate 55. Movement of the elevator block 118 raises or lowers the portion of the support plate 55 nearest the servo, depending upon whether the elevator block 118 travels up or down. Movement of the support plate 55 in most instances causes the plate 55 to yaw or roll slightly, which in turn causes the ball joint 140 to articulate. Optionally, a limit switch 150 may extend laterally from the elevator block 118, and upper and lower limit stops 155, 160 may actuate the limit switch 150 whenever the elevator block reaches predetermined top and bottom end-of-travel points determined by the locations of the limit stops 155, 160. A control signal cable 170 furnishes electrical control signals and power from a central controller 175 of the reactor of FIG. 1. The central controller 175 controls each of the three support servos 80, 85, 90. Placement of the three support servos 80, 85, 90 at equal intervals around the shoulder ring 40 enables the controller 175 to rotate the floating support plate 55 about any tilt axis oriented along any azimuthal angle θ relative to an axis of symmetry of the reactor chamber 16.

[0021] FIG. 5 depicts an integration of the reactor of FIG. 1 into a system for correcting for non-uniformity in etch rate distribution. The system includes a conventional measurement instrument or hardware 400 for measuring etch rate distribution across the surface of a workpiece or semiconductor wafer that has been subjected to a reactive ion etch process in the reactor of FIG. 1. A memory 410 stores the etch rate distribution data measured by the hardware 400. A computer 415 processes the etch rate distribution data stored in the memory 410 and deduces from that data an azimuthal angle θ defining the major axis of skew in the etch rate data. The computer 415 may further determine, from the magnitude of the skew (difference in etch rates across the major axis of skew) a desired tilt angle α by which the support plate 55 may be rotated about the major axis of skew lying along the angle θ that most likely to correct the skew. A computer 430 computes, from θ and α , the vertical deflection of the elevator block 118 of each of the three servos 80, 85, 90 that will produce the desired tilt angle α of rotation about the major axis of skew lying along the angle θ . This information is fed to the central controller 175, which then enables the three servos 80, 85, 90 to execute the desired motion of the floating support plate 55.

[0022] FIG. 6 depicts a method of operating the system of FIG. 5. First, a test wafer is processed in the reactor of FIG. 1 (block 500 of FIG. 6), and an etch rate distribution across the surface of the wafer is obtained (block 510). An azimuthal angle θ defining the major axis of skew is inferred from the etch rate distribution (block 520). Further, a tilt angle α about the major axis of skew is also inferred from the etch rate distribution (block 530) and specifically from the magnitude of the skew, or the difference between etch rates on opposite sides of the major axis of skew. If the magnitude of the skew is below a predetermined threshold or negligible (YES branch of block 535), then the skew correction process is skipped. Otherwise (NO branch of block 535), the vertical (Z-axis) movement of each one of the three servos 80, 85, 90 is computed from α and θ (block 540) and the servos are commanded accordingly (block 545). A new test wafer replaces the previous test wafer (block 550) and the process is repeated.

[0023] Continuing with the YES branch of block 535, if the skew magnitude is below a predetermined threshold or is negligible, then skew correction is halted. Any significant etch rate non-uniformity that remains is symmetrical (i.e.,

radial) so that the controller 175 may now correct the radial non-uniformity by adjusting the apportionment of RF power delivered to the concentric inner and outer coils 70, 75 (block 555 of FIG. 6). The controller 175 may perform this correction by directly adjusting the output power levels of the RF power

[0024] FIG. 7 depicts an X-Y-Z coordinate system used to locate the three servos 80, 85, 90, and defines the angles of rotation θ and α with respect to the X, Y and Z axes. Specifically, the angle θ is a rotation about the Z axis while the angle α is a rotation about the Y axis. The major axis of skew, inferred from the etch distribution data measured on a test wafer, lies in the X-Y plane of FIG. 7 and is defined with respect to the Y axis by a certain value of the angle θ . Skew correction is performed by tilting the support plate 55 about the skew axis by a particular tilt angle α . FIG. 8 depicts the X, Y, Z coordinates of the locations of the ball joints of the three servos 80, 85, 90 in one working example. The vertical motion required for each of the three servos may be computed directly from θ and α . Using the definitions of FIGS. 7 and 8, the computer 415 of FIG. 5 employs the following algorithms to compute the vertical motion of each of the three servos from the angles α and θ in units of inches:

$$Z(\text{motor } 1) = 10.2278(-\sin \alpha)(\cos \theta) + 5.905(\sin \alpha)(\sin \theta)$$

$$Z(\text{motor } 2) = 10.2278(\sin \alpha)(\cos \theta) + 5.905(\sin \alpha)(\sin \theta)$$

$$Z(\text{motor } 3) = 11.81(-\sin \alpha)(\sin \theta)$$

[0025] The foregoing algorithms were obtained by transforming the vector location of each servo by a rotation about the Z axis through an angle θ and by a rotation about the Y axis by an angle α .

[0026] FIG. 9 depicts an alternative embodiment, in which the floating support plate 55 of FIG. 1 is tilted by a single mechanism that replaces the three support servos 80, 85, 90. In the embodiment of FIG. 9, the radial width of the shoulder ring 40 is enlarged. A floating cradle 600 engages the support plate 55 near the periphery of the support plate 55. In one embodiment, the support plate 55 may be provided with a radial tab 55a at its periphery that engages the floating cradle 600. A roll axis block 610 is engaged with the floating cradle 600 and is constrained by a roll axis pin 615 that is fixed to the shoulder ring 40 to rotate about a roll axis 615a. A roll axis set screw 620 is threadably extends through and is threadably engaged with the roll axis block 610. The roll axis set screw 620 pushes against a top surface of the shoulder ring 40, and thereby controls the rotational position of the roll axis block 610 about the roll axis 615a. A yaw axis block 640 is engaged with the floating cradle 600 and is constrained by a yaw axis pin 650 that is fixed to the shoulder ring 40 to rotate about a yaw axis 650a. A yaw axis set screw 660 extends through and is threadably engaged with the shoulder ring 40 and pushes against a bottom surface of the yaw axis block 640, and thereby controls the rotational position of the yaw axis block 640 about the yaw axis 650a. By rotations of the two screws 620, 660, the support plate 55 may be rotated about a major axis lying along any desired azimuthal angle θ by any desired tilt angle α . The screws 620, 660 may be controlled by the controller 175 through actuators 670, 680, respectively. The computer 430 of FIG. 5 may be programmed to translate desired values of α and θ into corresponding rotations of the screws 620, 660, and the corresponding rotations of the

screws 620, 660 may be transmitted to the controller 175 to initiate corresponding rotations by the actuators 670, 680.

[0027] While the foregoing is directed to embodiments of the present invention, other and further embodiments of the invention may be devised without departing from the basic scope thereof, and the scope thereof is determined by the claims that follow.

1. A plasma reactor for processing a workpiece, comprising:

- a processing chamber enclosure defining a process chamber interior and comprising a chamber side wall and a chamber ceiling, and a workpiece holder inside said process chamber interior;
- a conductive RF enclosure overlying said ceiling and comprising an RF enclosure side wall and an RF enclosure top cover;
- a shoulder ring supported on said RF enclosure side wall;
- a floating support plate inside said conductive RF enclosure and located adjacent said shoulder ring;
- plural radially inner and outer RF plasma source power applicators suspended from said floating support plate in a space below said floating support plate and above said chamber ceiling;
- plural RF power sources, each of said plural RF power sources being coupled to a corresponding one of said plural RF plasma power applicators; and
- plural actuators fixed with respect to said shoulder ring and spaced about said shoulder ring at periodic intervals, each one of said plural actuators comprising an axially movable arm and a motor driving said movable arm in an axial direction and a rotatable joint having two joint ends, one of said joint ends being connected to said axially movable arm and the other of said joint ends being connected to a portion of said floating support plate adjacent said one actuator, whereby said floating plate is supported at respective plural locations by the rotatable joint of each respective one of said plural actuators.

2. The plasma reactor of claim 1 wherein said plural actuators constitute three actuators spaced at 120 degree intervals around said shoulder ring, whereby said actuators are able to tilt said floating support plate about a tilt axis oriented at any azimuthal angle θ .

3. The plasma reactor of claim 2 further comprising controller apparatus controlling said motor of each one of said plural actuators and programmed to compute axial motions of said plural actuators from desired values of said azimuthal angle θ of said tilt axis and a tilt angle α about said tilt axis.

4. The plasma reactor of claim 1 wherein each of said plural actuators is mounted on said shoulder ring and comprises a motor module containing said motor and a rail module supporting said movable arm side-by-side with said motor module and coupled to said motor module.

5. The plasma reactor of claim 4 further comprising a flexible conductive RF gasket ring coupled between said floating support plate and said shoulder ring.

6. The plasma reactor of claim 5 further comprising a metrology apparatus for measuring etch rate distribution on a test workpiece wherein said controller apparatus is further programmed to infer a major axis of skew from said etch rate distribution and define said tilt axis as said major axis of skew.

7. The plasma reactor of claim 6 wherein said controller apparatus controls power output levels of said plural RF power sources, said controller apparatus being programmed

to adjust said power output levels for improving uniformity of radial distribution of plasma ion density in said processing chamber.

8. The plasma reactor of claim **7** wherein said plural RF source power applicators comprise plural concentric helical conductor windings.

9. The plasma reactor of claim **7** wherein said floating support plate is spaced above said shoulder ring by a gap providing a limited range of rotation of said support plate.

10. The plasma reactor of claim **7** wherein said support plate comprises a surface extending radially inwardly from said RF enclosure side wall and underlying a peripheral portion of said floating support plate and separated therefrom by said gap.

11. The plasma reactor of claim **10** further comprising an RF impedance match apparatus between said floating support plate and said RF enclosure cover, said plural RF power sources being connected to said plural RF source power applicators through respective components of said RF impedance match apparatus.

12. A plasma reactor for processing a workpiece, comprising:

a processing chamber enclosure defining a process chamber interior and comprising a chamber side wall and a chamber ceiling, and a workpiece holder inside said process chamber interior;

a conductive RF enclosure overlying said ceiling and comprising an RF enclosure side wall and an RF enclosure top cover;

a shoulder ring supported on said RF enclosure side wall;

a floating support plate inside said conductive RF enclosure and located adjacent said shoulder ring;

plural radially inner and outer RF plasma source power applicators suspended from said floating support plate in a space below said floating support plate and above said chamber ceiling;

plural RF power sources, each of said plural RF power sources being coupled to a corresponding one of said plural RF plasma power applicators; and

a single actuator assembly fixed with respect to said shoulder ring and connected to a portion of said floating support plate adjacent a periphery of said floating support plate, said single actuator comprising a yaw rotation stage coupled to said shoulder ring for rotation about a yaw axis and a roll rotation stage coupled between said yaw rotation stage and said floating support plate for rotation about a roll axis transverse to said yaw axis, and actuator motors for rotating said yaw rotation stage and said roll rotation stage.

13. The plasma reactor of claim **12** wherein said actuator motors are able to tilt said floating support plate about a tilt axis oriented at an azimuthal angle θ , said plasma reactor further comprising controller apparatus controlling said actuator motors and programmed to compute motions of said yaw and roll rotation stages from desired values of said azimuthal angle θ of said tilt axis and a tilt angle α about said tilt axis.

14. The plasma reactor of claim **13** further comprising a flexible conductive RF gasket ring coupled between said floating support plate and said shoulder ring.

15. The plasma reactor of claim **14** wherein said floating support plate is spaced above said shoulder ring by a gap providing a limited range of rotation of said support plate.

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