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(54) **Title**: MULTIPLE FREQUENCY POWER FOR PLASMA CHAMBER ELECTRODE

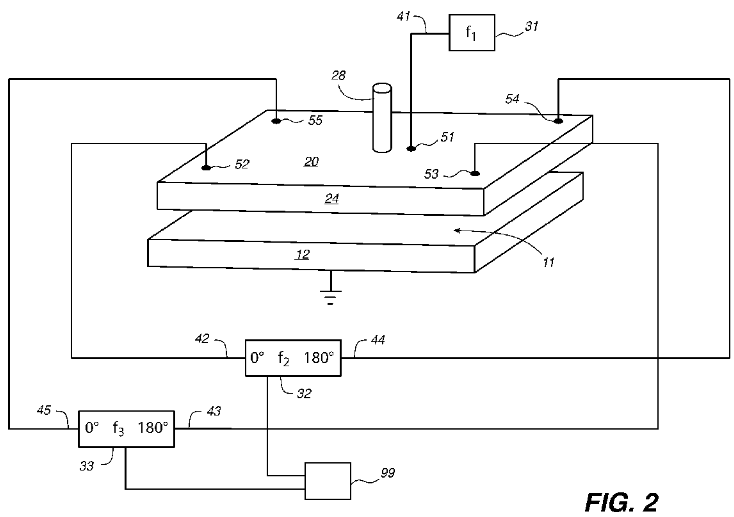

FIG. 2

(57) **Abstract**: First through fifth RF power signals are respectively coupled to first through fifth RF connection points on an electrode of a plasma chamber. The first, second and third RF power signals have distinct first, second and third frequencies, respectively. The second and fourth RF power signals have the same frequency and opposite phase. The third and fifth RF power signals have the same frequency and opposite phase. The second through fifth RF connection points are geometrically arranged as four successive vertices of a quadrilateral convex polygon. The first RF connection point is closer to the center of the electrode. The center strong spatial distribution of the electric field produced by the first RF power signal is offset by the center weak spatial distribution of the electric field produced by the second through fifth RF power signals. An alternative embodiment omits the third and fifth RF power signals and the third and fifth RF connection points.

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Multiple Frequency Power for Plasma Chamber Electrode

TECHNICAL FIELD

[0001] The invention relates generally to coupling RF power to an electrode of a plasma chamber used for fabricating electronic devices such as semiconductors, solar cells, displays, and solid state light emitting devices. The invention relates more specifically to improving the spatial uniformity by coupling different RF frequencies to different RF connection points on the electrode.

BACKGROUND ART

[0002] Plasma chambers commonly are used to perform processes for fabricating electronic devices such as semiconductors, solar cells, displays, and solid state light emitting devices. Such plasma fabrication processes include chemical vapor deposition of semiconductor, conductor or dielectric layers on the surface of a workpiece or etching of selected portions of such layers on the workpiece surface.

[0003] It is important for a plasma fabrication process to be performed with high spatial uniformity over the surface of the workpiece. For example, a deposition process should be performed so that the deposited material has uniform thickness and quality at all positions on the surface of the workpiece. Likewise, an etch process should etch material at a uniform rate at all such positions.

[0004] RF power can be capacitively coupled to plasma within a plasma chamber by coupling a source of RF power to an electrode positioned within, or adjacent to, the plasma chamber. If one-tenth the RF wavelength is less than the lateral width of the electrode, the plasma density, and hence the plasma fabrication process being performed on the workpiece, typically will suffer spatial non-uniformity if the RF power is coupled to only a single point on the electrode. In such cases, spatial uniformity of the plasma fabrication process typically can be improved by coupling the RF power to a plurality of spatially distributed RF connection points on the electrode.

[0005] US patent application publication no. 2009-0202741 A1 by Stimson et al., published 8/13/2009, has the same assignee as present application. It discloses two or more RF connection points that are spatially distributed in two dimensions on an electrode of a plasma chamber, wherein different RF power signals having the same frequency and different phase offsets are coupled to different RF connection points. The phase offsets are disclosed as either static or time-varying.

[0006] US patent application publication no. 2010-0245214 A1 by Baek, published 9/30/2010, has the same assignee as present application. It discloses two or more RF power signals of different frequencies coupled to different RF connection points that are spatially distributed in two dimensions on an electrode of a plasma chamber. The difference between the respective frequencies of the RF power signals is less than any of the RF power frequencies and produces an interference pattern.

SUMMARY OF THE INVENTION

[0007] One aspect or embodiment of the invention comprises first through fifth RF power signals that are respectively coupled to first through fifth RF connection points on an electrode of a plasma chamber.

[0008] The first, second and third RF power signals have first, second and third frequencies, respectively, that are different from each other. The second and fourth RF power signals have the same frequency and opposite phase. The third and fifth RF power signals have the same frequency and opposite phase. In defining the invention, “opposite phase” can mean a phase difference of 180 degrees, or it can mean a phase difference in the range of 90 degrees to 270 degrees.

[0009] The second through fifth RF connection points are geometrically arranged as four successive vertices of a quadrilateral convex polygon. (Consequently, the second and fourth RF connection points are opposite each other, and the third and fifth RF connection points are opposite each other.)

[0010] Preferably the first RF connection point is positioned so that it is the RF connection point that is closest to the center of the electrode. In other words, the center of the electrode preferably is closer to first RF connection point than to any of the second through fifth RF connection points. Preferably, the first RF connection point is closer to the center of the electrode than to the lateral edges of the electrode. Alternatively, the position of the first RF connection point is relatively insignificant if the first RF frequency is low enough that the first RF power signal has a quarter-wavelength that is greater than the greatest lateral width of the electrode.

[0011] Preferably, each of the second through fifth RF connection points is positioned closer to a lateral edge of the electrode than to the center of the electrode. If the electrode has a rectangular surface, the second through fifth RF connection points preferably are positioned adjacent the four respective corners of the rectangular surface or adjacent the four respective sides of the rectangular surface.

[0012] Because RF power signals having the same frequency and opposite phase are coupled to opposite RF connection points, they at least partially cancel out each other near the center of the electrode. Therefore, the second through fifth RF power signals combine to produce an electric field in the plasma chamber that is minimum near the center of the electrode and typically is maximum near the lateral edges of the electrode. In contrast, the first RF power signal produces an electric field in the plasma chamber that is maximum near the center of the electrode and typically is minimum near the lateral edges of the electrode.

[0013] Advantageously, the center strong spatial distribution of the electric field produced by the first RF power signal is offset by the center weak spatial distribution of the electric field produced by the second through fifth RF power signals. Therefore, the electric fields described in the preceding paragraph produce a combined electric field that typically has better spatial uniformity than the electric field produced by any of the RF power signals individually.

[0014] The ratio between the power level of the first RF signal to the total of the power levels of the second through fifth RF signals affects the ratio between the aforesaid center strong and center weak electric field distributions. Preferably, such ratio is adjusted or established so as to optimize such spatial uniformity.

[0015] If the first through fifth RF connection points are on a surface of the electrode, all references to "the center of the electrode" in defining the invention can be replaced with "the center of said surface of the electrode".

[0016] A second aspect or embodiment of the invention comprises first, second and third RF power signals that are respectively coupled to first, second and third RF connection points on an electrode of a plasma chamber. The first RF connection point is between the second and third RF connection points, and the center of the electrode is closer to the first RF connection point than to the second and third RF connection points. Preferably, each of the second and third RF connection points is closer to a respective lateral edge of the electrode than to the center of the electrode. The first RF connection point is between the second and third RF connection points and is closer to the center of the electrode than to said respective lateral edges of the electrode.

[0017] The first and second RF power signals have different frequencies. The second and third RF power signals have the same frequency and are opposite in phase.

[0018] Because the second and third RF power signals are opposite in phase and are coupled to respective RF connection points at opposite sides of the first RF connection point (preferably at opposite sides of the center of the electrode), they at least partially cancel out each other near the first RF connection point and near the center of the electrode. Therefore, they combine to produce an electric field in the plasma chamber that typically is maximum near the lateral edges of the electrode and minimum near the center of the electrode. In contrast, the first RF power signal produces an electric field in the plasma chamber that typically is maximum near the center of the electrode and minimum near the lateral edges of the electrode.

[0019] Advantageously, the center strong spatial distribution of the electric field produced by the first RF power signal is offset by the typically center weak spatial distribution of the electric field produced by the second and and third RF power signals. Therefore, the electric fields described in the preceding paragraph produce a combined electric field that typically has better spatial uniformity than the electric field produced by any of the three RF power signals individually.

[0020] The ratio between the power level of the first RF signal to the total of the power levels of the second and third RF signals affects the ratio between the aforesaid center strong and center weak electric field distributions. Preferably, such ratio is adjusted or established so as to optimize such spatial uniformity.

BRIEF DESCRIPTION OF THE DRAWINGS

[0021] Figure 1 is a partially schematic, sectional side view of a plasma chamber according to the invention.

[0022] Figure 2 is a partially schematic, perspective view of a plasma chamber according to the invention.

[0023] Figure 3 is a partially schematic, perspective view of an alternative embodiment in which the RF connection points are adjacent the sides of the electrode.

BEST MODE FOR CARRYING OUT THE INVENTION

1. Overview of Plasma Chamber

[0024] Figures 1 and 2 show a plasma chamber according to the invention. A susceptor 12 supports a workpiece at an area within the plasma chamber referred to as the "workpiece support area" 10. The plasma chamber is intended to subject the workpiece to a plasma process step for fabricating on the workpiece electronic devices such as semiconductor devices, solar cells, displays, and solid state light emitting devices. Examples of a workpiece that would be processed within the plasma chamber include a rectangular glass substrate on which solar cells or flat panel displays are fabricated or a circular semiconductor wafer on which integrated circuits are fabricated.

[0025] The plasma chamber has an electrically conductive chamber wall 14–18, preferably aluminum, that provides a vacuum enclosure for the chamber interior. In the illustrated embodiment, the chamber side wall 14 and chamber bottom wall 16 are implemented as a unitary wall. The chamber wall also includes a top wall 18. All portions of the chamber wall are connected together electrically and are electrically grounded.

[0026] In performing a plasma process on the workpiece, one or more process gases are dispensed into the interior 11 of the chamber through an electrode 20–24 that also functions as a gas inlet manifold. The gas inlet manifold includes a manifold back wall 20, a showerhead 22 (also called a gas distribution plate or diffuser), and a suspension 24, all of which collectively enclose a volume which constitutes the interior 26 of the gas inlet manifold.

[0027] A gas inlet conduit 28 extends through the center of the manifold back wall 20. A gas source, not shown, supplies process gases to the upper end of the gas inlet conduit. The process gases flow from the gas inlet conduit into the interior 26 of the gas inlet manifold, and then are dispensed into the plasma chamber through numerous openings in the showerhead 22.

[0028] At least a portion of the weight of the showerhead 22 is supported by the suspension 24, which is supported by the gas inlet manifold back wall 20, which is supported by the chamber side wall 14. The suspension 24 preferably is flexible so as to accommodate radial expansion and contraction of the showerhead as the temperature of the showerhead rises and falls. The suspension 24 has an upper end connected to the gas inlet manifold back wall 20 and a lower end connected to the rim at the periphery of the showerhead 22. The latter connection can be either static or sliding. For example, a sliding connection can be implemented by resting the showerhead rim on the lower end of the suspension.

[0029] If the showerhead is rectangular as in the illustrated embodiment, the vertically extending portion of the suspension 24 preferably consists of four flexible sheets respectively connected to the four sides of the rectangular showerhead 22. Each sheet extends vertically between one side of the rectangular showerhead and a corresponding side of the rectangular back wall 20.

[0030] The electrode 20–24, in addition to its function of dispensing gas as described above, functions to couple RF power to the plasma within the interior 11 of the plasma chamber. The manifold back wall 20, showerhead 22 and suspension 24 are electrically conductive, preferably aluminum. Dielectric liners 19 electrically and mechanically separate the RF powered electrode 20–24 from the electrically grounded chamber wall 14–18.

[0031] Although the electrode 20–24 in the illustrated embodiment is a gas inlet manifold, the scope of invention includes RF connection points on any conventional plasma chamber electrode that can capacitively couple RF power to a plasma within the plasma chamber, regardless of whether the electrode has a gas distribution function. In other words, the electrode need not be part of a gas inlet manifold and need not include a showerhead.

[0032] Furthermore, the electrode can be outside the chamber wall 14–18 if it is adjacent a portion of the chamber wall that is dielectric, thereby permitting RF power to be capacitively coupled from the electrode to the plasma within the chamber. Because the electrode can be inside or outside the chamber wall, the electrode is described herein as an electrode "of" the chamber rather than an electrode "in" the chamber.

[0033] The manifold gas wall 20, the showerhead 22 are each parallel to the workpiece support area 10. Consequently the electrode 20–24, considered in its entirety as a single component, also is parallel to the workpiece support area.

[0034] In describing the invention we refer to lateral and longitudinal dimensions of the plasma chamber or, equivalently, to X, Y and Z axes of the plasma chamber. We define the longitudinal dimension of the plasma chamber — in other words, the Z-axis of the plasma chamber — as extending perpendicular to and between the electrode 20–24 and the workpiece support area 10. In Figures 1– 3, the longitudinal dimension and the Z-axis of the plasma chamber are in the vertical direction of the drawing sheet.

[0035] We define the two lateral dimensions of the plasma chamber — in other words, the X-axis and Y-axis of the plasma chamber — as extending perpendicular to the longitudinal dimension or Z-axis. An equivalent definition is that the two lateral dimensions of the plasma chamber — in other words, the X-axis and Y-axis of the plasma chamber — extend parallel to the electrode 20–24 and to the workpiece support area 10.

[0036] We define the two lateral dimensions, the longitudinal dimension and the X, Y and Z-axes of the electrode 20–24 as respectively parallel to the two lateral dimensions, the longitudinal dimension and the X, Y and Z-axes of the plasma chamber. When we refer to the lateral width of the electrode 20–24, we mean the width of the electrode along a direction parallel to the X-Y plane, i.e., perpendicular to the Z-axis. When we refer to the lateral edges of the electrode 20–24, we mean the outer boundaries of the electrode in the X-Y plane. For example, in the embodiment illustrated in Figures 1–3, the lateral edges of the electrode are the four vertically-extending sides at the perimeter of the manifold back wall 20.

[0037] In the illustrated embodiments, the workpiece area 10 is rectangular, and both the upper and lower surfaces of the electrode 20–24 are in the shape of a rectangle having a length and a width such that the length is greater than or equal to the width. In that case we define the X-axis and Y-axis as parallel to the length and width dimensions, respectively, of the electrode. The X-axis is the horizontal direction of the drawing sheet in Figures 1–3. The Y-axis is perpendicular to the drawing sheet in Figure 1.

2. Three Frequencies Coupled to Five RF Connection Points

[0038] A first RF power source 31 produces a first RF power signal 41 having a first frequency f_1. A second RF power source 32 produces second and fourth RF power signals 42, 44 that are opposite in phase and have a second frequency f_2. A third RF power source 33 produces third and fifth RF power signals 43, 45 that are opposite in phase and have a third frequency f_3.

[0039] The three frequencies f_1, f_2 and f_3 should be distinct (i.e., different from each other) to avoid creating a stationary interference pattern that would diminish the spatial uniformity of the electric field in the plasma.

[0040] We use the term "RF connection point" to mean a position on an electrode of a plasma chamber at which RF power is connected to the electrode. The first through fifth RF power signals 41–45 are respectively coupled to first through fifth RF connection points 51–55 on the electrode 20–24.

[0041] The second through fifth RF connection points 52–55 are geometrically arranged as four successive vertices of a quadrilateral convex polygon. Consequently, the second and fourth RF connection points 52, 54 are opposite each other, and the third and fifth RF connection points 53, 55 are opposite each other.

[0042] Consequently, the first through fifth RF connection points 51–55 are spatially distributed along both the X-axis and the Y-axis, i.e., along both lateral dimensions of the electrode. Additionally, no three of the second through fifth RF connection points 52–55 are collinear.

[0043] If the RF connection points are on a rectangular surface of the electrode 20–24, the second through fifth RF connection points preferably are positioned adjacent the four respective corners of the rectangular surface (as in Figure 2) or adjacent the four respective sides of the rectangular surface (as in Figure 3). In the illustrated embodiments, the rectangular surface is the rear (i.e., upper) surface of the manifold back wall 20 of the electrode 20–24.

[0044] Preferably the first RF connection point 51 is positioned so that it is the RF connection point that is closest to the center of the electrode. In other words, the center of the electrode preferably is closer to first RF connection point 51 than to any of the second through fifth RF connection points 52–55. (The phrases "closest to the center" and "closer to the center" are intended to include the first RF connection point being "at the center" of the electrode.) Alternatively, the position of the first RF connection point is relatively insignificant if the first RF frequency is low enough that the first RF power signal has a quarter-wavelength that is greater than the greatest lateral width of the electrode 20–24.

[0045] In the embodiment of the invention shown in Figures 1 and 2, the RF connection points 51–55 are on the rear (i.e., upper) surface of the manifold back wall 20 of the electrode 20–24. The second through fifth RF connection points 52–55 are respectively adjacent to the four successive corners of the rectangular rear surface of the manifold back wall 20. The first RF connection point 51 is the RF connection point that is closest to, or at, the center of said rear surface.

[0046] Instead of the second through fifth RF connection points 52–55 being adjacent the four corners of the rectangular electrode as shown in Figure 2, Figure 3 shows a useful alternative design in which the second through fifth RF connection points 52–55 are adjacent the four successive sides of the lateral perimeter of the rectangular electrode 20–24.

[0047] Figures 2 and 3 show all the RF power sources 31–33 and RF connection points 51–55. Figure 1 only shows the RF connection point 51 near the center of the electrode and its corresponding RF power source 31 because Figure 1 is a sectional view of the Figure 2 design taken at a vertical plane that bisects the left and right side walls 14 of the plasma chamber.

[0048] RF power flows from the outputs of the RF power sources 31–33 to the RF connection points 51–55 on the manifold back wall 20, then along the manifold back wall to the four suspension walls 24 at the four sides of the manifold back wall, and then along the four suspension walls to the four sides of the showerhead 22. The RF power is coupled from the showerhead to a plasma between the showerhead and the susceptor.

[0049] The circuitry for coupling an RF power signal to an RF connection point on an electrode preferably includes an RF impedance matching network electrically connected between the output of an RF power supply and the RF connection point. When referring to any of the RF power sources 31–33, we use the term “RF power source” to include an RF power supply and, optionally but preferably, a respective RF impedance matching network between the output of the RF power supply and the each respective output of the RF power source.

[0050] Because RF power signals having the same frequency and opposite phase are coupled to opposite RF connection points, they at least partially cancel out each other near the center of the electrode. Therefore, the second through fifth RF power signals combine to produce an electric field in the plasma chamber that is minimum near the center of the electrode and typically is maximum near the lateral edges of the electrode.

[0051] More specifically, because the second and fourth RF power signals 42, 44 having the same frequency and opposite phase are coupled to the second and fourth RF connection points 52, 54 that are opposite each other, they at least partially cancel out each other near the center of the electrode. Therefore, the second and fourth RF power signals 42, 44 combine to produce an electric field in the plasma chamber that is minimum near the center of the electrode and typically is maximum near the respective corners or side edges of the electrode adjacent the second and fourth RF connection points 52, 54.

[0052] Similarly, because the third and fifth RF power signals 43, 45 having the same frequency and opposite phase are coupled to the third and fifth RF connection points 53, 55 that are opposite each other, they at least partially cancel out each other near the center of the electrode. Therefore, the third and fifth RF power signals 43, 45 combine to produce an electric field in the plasma chamber that is minimum near the center of the electrode and typically is maximum near the respective corners or side edges of the electrode adjacent the third and fifth RF connection points 53, 55.

[0053] In contrast, the first RF power signal produces an electric field in the plasma chamber that is maximum near the center of the electrode and typically is minimum near the lateral edges of the electrode.

[0054] Advantageously, the center strong spatial distribution of the electric field produced by the first RF power signal 41 is offset by the typically center weak spatial distribution of the electric field produced by the second through fifth RF power signals 42–45. Therefore, the electric fields described in the three preceding paragraphs produce a combined electric field that typically has better spatial uniformity than the electric field produced by any of the three RF power sources 31–33 individually.

[0055] The ratio between the power level of the first RF signal 41 to the total of the power levels of the second through fifth RF signals 42–45 affects the ratio between the aforesaid center strong and center weak electric field distributions. Preferably, such ratio is adjusted or established so as to optimize such spatial uniformity.

[0056] In one simulation we performed, the spatial uniformity of the electric field in the interior 11 of the plasma chamber was optimized when the total of the power levels of the second through fifth RF power signals 42–45 was 20 percent of the power level of the first RF power signal 41. In that simulation, the first RF power signal 41 had frequency $f_1 = 13$ MHz, the second and fourth RF power signals 42, 44 had frequency $f_2 = 40.67$ MHz, and the third and fifth RF power signals 43, 45 had frequency $f_3 = 40.68$ MHz.

[0057] The second through fifth RF connection points 52–55 are arranged geometrically as the four vertices of a rectangle in the illustrated embodiment. However, to compensate for asymmetries in the plasma chamber, it may be possible to improve spatial uniformity of the plasma density, or to improve spatial uniformity of the fabrication process performed on the workpiece, by arranging the RF connection points in a geometric pattern other than a rectangle. The positions of the second through fifth RF connection points 52–55 can be defined more generally as the successive vertices of a quadrilateral convex polygon, i.e., a convex tetragon.

[0058] In the embodiments described above, each of the second and third RF power sources 32, 33 were described as producing two RF signals having the same frequency and opposite phase. More broadly, the two RF signals having opposite phase may have a phase difference of 180 degrees, but this is not required. If their phase difference is in the range of 90 degrees to 270 degrees, they still will produce partial cancellation of their respective electric fields near the center of the plasma.

[0059] Therefore, the invention more broadly encompasses the second and fourth RF signals 42, 44 having the same frequency f_2 and a first phase difference in the range of 90 degrees to 270 degrees; and the third and fifth RF signals 43, 45 having the same frequency f_3 and a second phase difference in the range of 90 degrees to 270 degrees.

[0060] The values of the first and second phase differences affect the relative values of the respective time-averaged electric field strengths near the center and edges of the electrode. Therefore, the values of the two phase differences can be established so as to improve the time-averaged spatial uniformity of the plasma density in the interior of the plasma chamber or to improve the spatial uniformity of a fabrication process to be performed on the workpiece in the chamber. The optimum values of the two phase differences will depend on the dimensions of the plasma chamber and on the second and third RF frequencies f_2 and f_3.

3. Two Frequencies Coupled to Three RF Connection Points

[0061] A second aspect or embodiment of the invention requires only two RF frequencies instead of three frequencies. Its implementation is illustrated by Figures 1–3, except with the following components omitted: the third RF power source 33, the third and fifth RF power signals 43, 45 produced by the third RF power source, and the third and fifth RF connection points 53, 55.

[0062] A first RF power source 31 produces a first RF power signal 41 having a first frequency f_1. A second RF power source 32 produces second and fourth RF power signals 42, 44 that are opposite in phase and have a second frequency f_2 that is different from the first frequency. The first, second and fourth RF power signals 41, 42, 44 are respectively coupled to first, second and fourth RF connection points 51, 52, 54 on an electrode 20–24 of a plasma chamber.

[0063] (The summary of this second aspect or embodiment of the invention in the "Summary of the Invention" section of this patent specification refers to the fourth RF power signal 44 and the fourth RF connection point 54 as the third RF power signal and third RF connection point, respectively, because the "Summary of the Invention" does not reference the drawing reference numbers.)

[0064] The first RF connection point 51 is closer to the center of the electrode than to any of the lateral edges (i.e., the lateral perimeter) of the electrode. Each of the second and fourth RF connection points 52, 54 is closer to a respective lateral edge of the electrode than to the center of the electrode. The second and fourth RF connection points are at opposite sides of the center of the electrode.

[0065] Because the second and fourth RF power signals 42, 44 are opposite in phase and are coupled to respective RF connection points at opposite sides of the center of the electrode, they at least partially cancel out each other near the center of the electrode. Therefore, they combine to produce an electric field in the plasma chamber that is minimum near the center of the electrode and typically is maximum near the lateral edges of the electrode. In contrast, the first RF power signal 41 produces an electric field in the plasma chamber that is maximum near the center of the electrode and typically is minimum near the lateral edges of the electrode.

[0066] Advantageously, the center strong spatial distribution of the electric field produced by the first RF power signal 41 is offset by the center weak spatial distribution of the electric field produced by the combination of the second and and fourth RF power signals 42, 44. Therefore, the electric fields described in the preceding paragraph produce a combined electric field and plasma density in the interior 11 of the plasma chamber that typically has better spatial uniformity than the electric field and plasma density that would be produced by any of the three RF power signals individually.

[0067] The features described in the subsequent sections of this patent specification apply to all the aspects and embodiments of the invention described above, including the first aspect with three frequencies coupled to five connection points and the second aspect with two frequencies coupled to three connection points.

4. RF Power Wavelengths and Electrode Width

[0068] If the respective half-wavelengths of the second through fifth RF power signals 42–45 are greater than the lateral width of the electrode, the electric field distribution will be the “typical” distribution described in the preceding paragraphs. If the respective half-wavelengths are less than the lateral width of the electrode, the locations where the electric field is maximum will be shifted toward the center of the electrode. If the respective half-wavelengths are less than one-half the lateral width of the electrode, typically the electric field distribution will have a relative maximum at more than one location between the center and the lateral edge of the electrode.

[0069] It is preferred, but not required, for each pair of opposite phase RF signals 42, 44 or 43, 45 to produce an electric field distribution that does not have a relative maximum at more than one location between the center and the lateral edge of the electrode in order to achieve a simpler electric field distribution that is easier to model mathematically. Consequently, it is preferred, but not required, that each of the second through fifth RF power signals 42–45 has a wavelength that is greater than the greatest lateral width of the electrode; or, more alternatively, greater than the greatest lateral width of the electrode surface that contains the RF connection points 52–55.

5. Compensating for Asymmetry in Plasma Chamber

[0070] The first RF connection point 51 can be positioned at the center of the electrode 20–24, or it can be positioned off-center.

[0071] It can be advantageous to establish the first RF connection point 51 at a position that is offset from the center of the electrode in a direction and a distance chosen to compensate for asymmetry in the plasma chamber. For example, if the plasma chamber has an asymmetry caused by a workpiece passageway or slit valve (not shown) at one side of the plasma chamber, the first RF connection point can be offset from the center of the electrode in a direction toward the workpiece passageway. In each of Figures 1–3, this is illustrated by the first RF connection point 51 being offset toward the right side of the chamber.

[0072] In one possible embodiment of the first RF connection point 51 being offset from the center of the electrode, the first RF connection point 51 can be the same as one of the second through fifth RF connection points 52–55. In other words, the first RF power signal 41 can be connected to the same RF connection point as one of the second through fifth RF power signals 42–45.

[0073] The second through fifth RF power signals 42–45 can have equal levels of RF power, but this is not required. To compensate for asymmetries in the plasma chamber, it may be desirable to establish different respective levels of RF power for the respective second through fifth RF power signals 42–45 in order to optimize the spatial uniformity of the plasma density or the spatial uniformity of one or more properties of a layer being fabricated on the workpiece 10.

6. Time-Varying Frequency or Phase

[0074] Each of the first, second and third frequencies f_1, f_2 and f_3 can be static values. Alternatively, one or more of the first, second and third frequencies f_1, f_2 and f_3 can be time-varying. In other words, any one or more of the RF power sources 31, 32, 33 can produce a respective RF power signal 41, 42, 43 having a respective frequency f_1, f_2 or f_3 that is time-varying.

[0075] Each of the first and second phase differences can be static values, or one or both can be time-varying. In other words, the second RF power source 32 optionally can produce a first time-varying phase difference between the second and fourth RF signals 42, 44. Likewise, the third RF power source 33 optionally can produce a second time-varying phase difference between the third and fifth RF signals 43, 45.

[0076] Providing such time-varying phase difference or frequency will cause the spatial distribution of the electric field and plasma density in the interior 11 of the plasma chamber to vary with time. This can be advantageous to produce a time-averaged spatial uniformity of the electrical field and plasma density that is more uniform than the spatial uniformity at any instant in time.

7. RF Power Sources, Phase Shift Circuits and Controller

[0077] In any of the embodiments of the invention, the phase shifts described above optionally can be implemented by including one or more conventional RF phase shift circuits within the second and third RF power sources 32, 33. For example, the second RF power source 32 can include an RF power supply whose output is electrically connected to the input of an RF phase shift circuit, wherein the output of the RF power supply is connected to supply the second RF power signal 42 to the second RF connection point 54, and the output of the RF phase shift circuit is connected to supply the fourth RF power signal 44 to the fourth RF connection point 54.

[0078] If the desired phase difference between the second and fourth RF power signals is 180 degrees, the phase shift circuit within an RF power source 32 or 33 can be, for example, a conventional RF transformer.

[0079] As an alternative example, the phase shift circuit within an RF power source 32 or 33 can be implemented by an RF impedance matching network within that RF power source 32 or 33. For example, the second RF power source 32 can include an RF power supply whose output is electrically connected to the input of an RF impedance matching network that has two outputs that supply the second and fourth RF power signals, respectively.

[0080] Furthermore, the three RF power sources 31–33 need not be separate hardware components. By way of example but not limitation, the three RF power sources can be implemented by a single waveform generator, such as a conventional direct digital synthesizer, capable of producing all five RF power signals 41–45. Such waveform generator also can produce the phase shifts between the pairs of opposite phase RF power signals 42, 44 and 43,45, thereby eliminating any need for a separate phase shift circuit.

[0081] The invention optionally can include a conventional controller 99, such as a conventional programmable computer, which can be programmed to send control signals to each of the RF power sources 31–33 to control their respective static or time-varying frequencies f_1–f_3 and, optionally, to control the first and second static or time-varying phase differences respectively produced by the second and third RF power sources 32, 33. Furthermore, a conventional programmable computer also can perform the functions of a direct digital synthesizer as described in the preceding paragraph, so that a single computer can perform the combined functions of of the three RF power sources 31–33 and the controller 99.

CLAIMS

1. Apparatus for coupling RF power to a plasma chamber comprising:

a first RF power source that produces a first RF power signal having a first frequency;

a second RF power source that produces second and fourth RF power signals having a second frequency;

a third RF power source that produces third and fifth RF power signals having a third frequency;

a plasma chamber electrode having first through fifth RF connection points that are respectively connected to receive the first through fifth RF power signals, wherein the second through fifth RF connection points are geometrically arranged as four successive vertices of a quadrilateral convex polygon;

wherein the first, second and third frequencies are distinct;

wherein the second and fourth RF power signals have a phase difference in the range of 90 degrees to 270 degrees; and

wherein the third and fifth RF power signals have a phase difference in the range of 90 degrees to 270 degrees.

2. The apparatus of claim 1, wherein:

each of the second through fifth RF connection points is closer to a lateral edge of the electrode than to the center of the electrode; and

the first RF connection point is closer to the center of the electrode than to said respective lateral edges of the electrode.

3. The apparatus of claim 1, wherein:

the center of the electrode is closer to first RF connection point than to any of the second through fifth RF connection points.

4. The apparatus of claim 1, wherein:

each of the first through fifth RF connection points is on a surface of the electrode; and

the center of said surface of the electrode is closer to first RF connection point than to any of the second through fifth RF connection points.

5. The apparatus of claim 1, wherein:

the first RF power signal has a quarter-wavelength that is greater than the greatest lateral width of the electrode.

6. The apparatus of claim 1, wherein:

each of the second through fifth RF power signals has a wavelength that is greater than the greatest lateral width of the electrode.

7. The apparatus of claim 1, wherein:

the phase difference between the second and fourth RF power signals is 180 degrees.

8. The apparatus of claim 7, wherein:

the phase difference between the third and fifth RF power signals is 180 degrees.

9. The apparatus of claim 1, wherein:

the phase difference between the second and fourth RF power signals is time-varying.

10. The apparatus of claim 1, wherein:

the phase difference between the second and fourth RF power signals is static; and the phase difference between the third and fifth RF power signals is static.

11. The apparatus of claim 1, wherein:

a least one of the first, second and third frequencies is time-varying.

12. The apparatus of claim 1, wherein:

the electrode includes a rectangular surface having four corners; and

the second through fifth RF connection points are positioned adjacent the four respective corners of said rectangular surface.

13. The apparatus of claim 1, wherein:

the electrode includes a rectangular surface having four sides; and

the second through fifth RF connection points are positioned adjacent the four respective sides of said rectangular surface.

14. The apparatus of claim 1, wherein:

the electrode includes a gas inlet manifold back wall, a showerhead, and a suspension connected between the gas inlet manifold back wall and the showerhead so as to support at least a portion of the weight of the showerhead; and

each of the RF connection points is on the gas inlet manifold back wall.

15. Apparatus for coupling RF power to a plasma chamber comprising:

a first RF power source that produces a first RF power signal having a first frequency;

a second RF power source that produces second and third RF power signals having a second frequency that is distinct from the first frequency;

a plasma chamber electrode having first, second and third RF connection points that are respectively connected to receive the first, second and third RF power signals;

wherein:

the first RF connection point is between the second and third RF connection points;

the center of the electrode is closer to the first RF connection point than to the second and third RF connection points; and

the second and third RF power signals have a phase difference in the range of 90 degrees to 270 degrees.

16. The apparatus of claim 15, wherein:

each of the second and third RF connection points is closer to a respective lateral edge of the electrode than to the center of the electrode; and

the first RF connection point is closer to the center of the electrode than to said respective lateral edges of the electrode.

17. The apparatus of claim 15, wherein:

the first RF power signal has a quarter-wavelength that is greater than the greatest lateral width of the electrode.

18. The apparatus of claim 15, wherein:

each of the second and third RF power signals has a wavelength that is greater than the greatest lateral width of the electrode.

19. The apparatus of claim 15, wherein:

the phase difference between the second and third RF power signals is 180 degrees.

20. The apparatus of claim 15, wherein:

the phase difference between the second and third RF power signals is time-varying.

21. The apparatus of claim 15, wherein:

a least one of the first and second frequencies is time-varying.

22. The apparatus of claim 15, wherein:

the electrode includes a rectangular surface having four sides; and

the second and third RF connection points are positioned adjacent two opposite sides of said rectangular surface.

23. A method for coupling RF power to a plasma chamber comprising the steps of:

producing a first RF power signal having a first frequency;

producing second and fourth RF power signals having a second frequency that is distinct from the first frequency;

producing third and fifth RF power signals having a third frequency that is distinct from the first and second frequencies;

providing a plasma chamber electrode having first through fifth RF connection points that are respectively connected to receive the first through fifth RF power signals, wherein the second through fifth RF connection points are geometrically arranged as four successive vertices of a quadrilateral convex polygon;

wherein the second and fourth RF power signals have a phase difference in the range of 90 degrees to 270 degrees; and

wherein the third and fifth RF power signals have a phase difference in the range of 90 degrees to 270 degrees.

24. A method for coupling RF power to a plasma chamber comprising the steps of:

producing a first RF power signal having a first frequency;

producing second and third RF power signals having a second frequency that is distinct from the first frequency;

providing a plasma chamber electrode having first, second and third RF connection points that are respectively connected to receive the first, second and third RF power signals;

wherein:

the first RF connection point is between the second and third RF connection points;

the center of the electrode is closer to the first RF connection point than to the second and third RF connection points; and

the second and third RF power signals have a phase difference in the range of 90 degrees to 270 degrees.

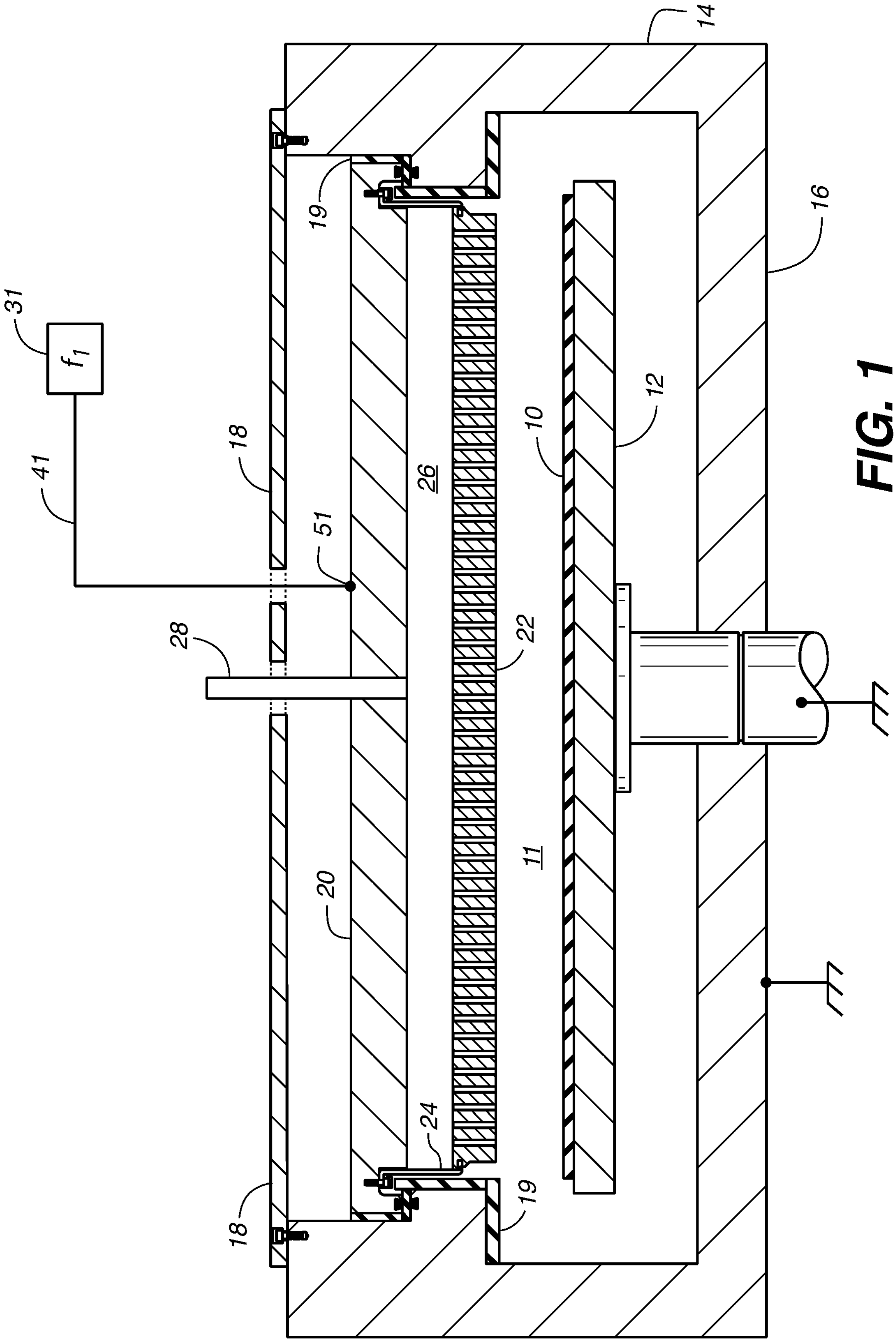
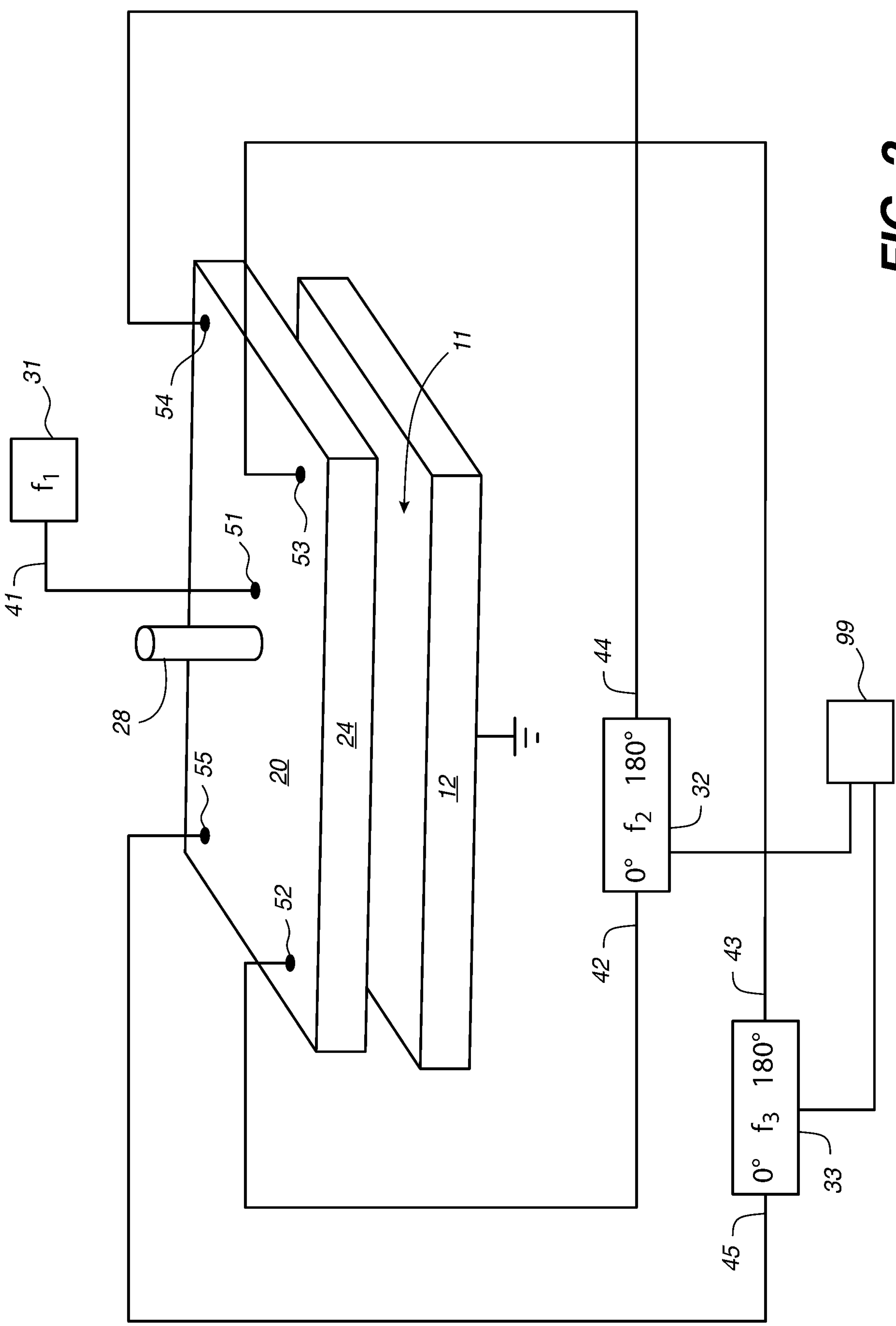


FIG. 1


31
f_1
41
51
54
53
11
28
55
20
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12
52
44
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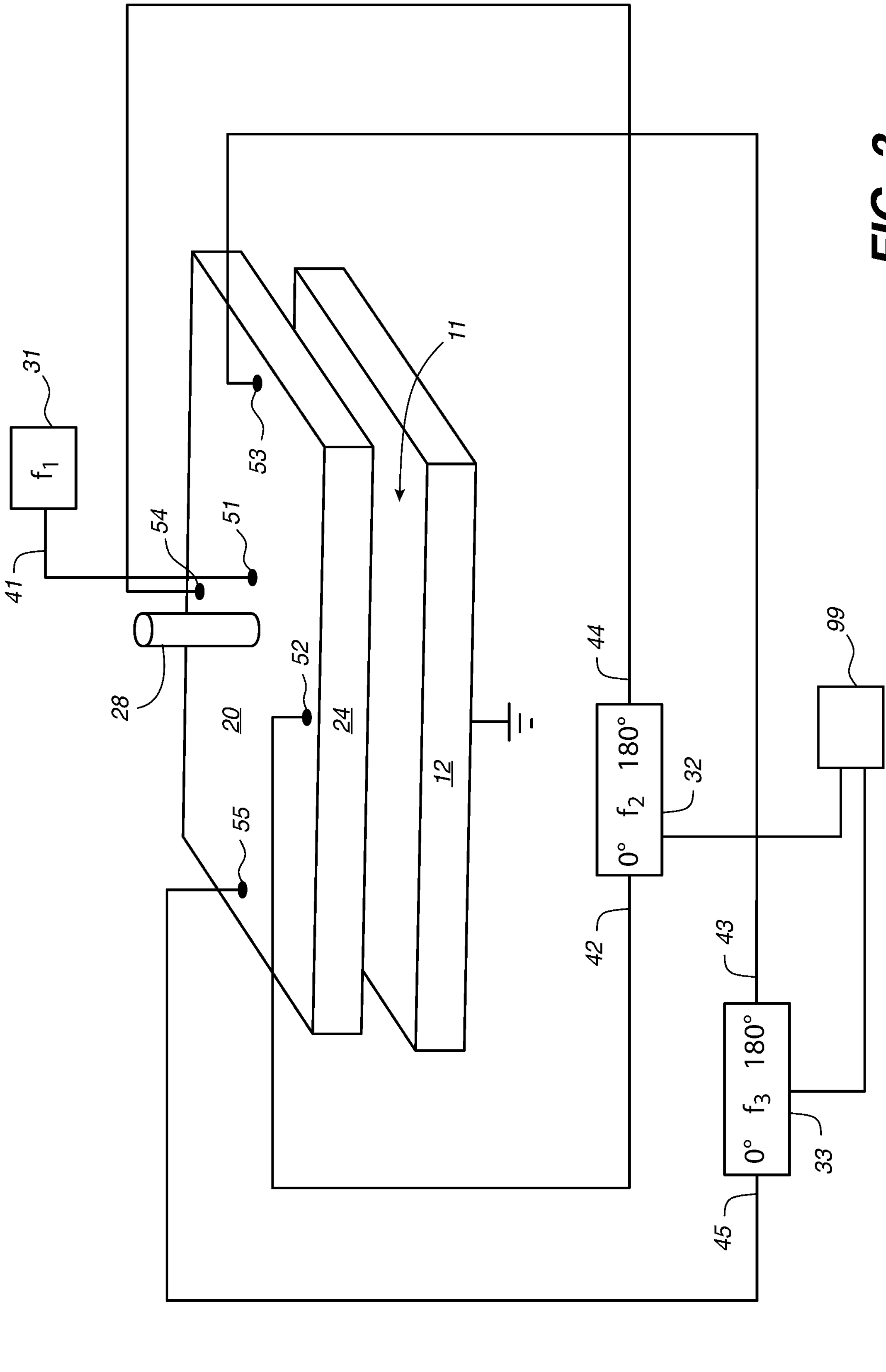
32
99
42
43
0° f_3 180°
33
45

FIG. 2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54
51
53
11
28
20
24
52
12
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44
0° f_2 180°
32
99
42
43
0° f_3 180°
33
45

FIG. 3