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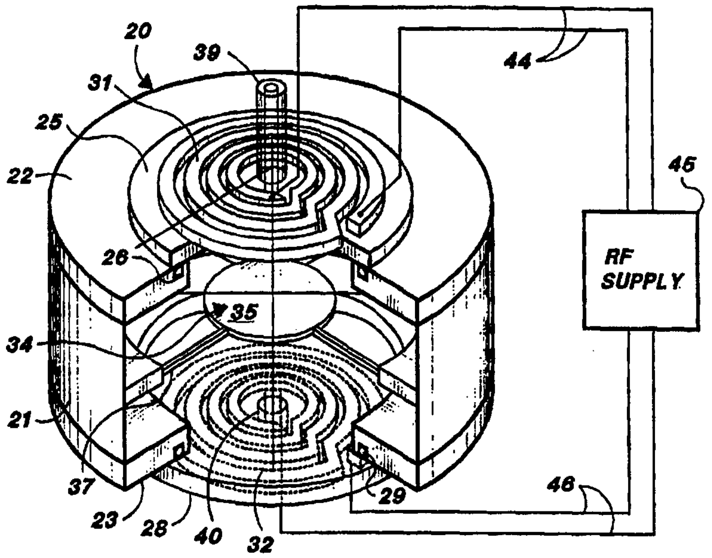

(57) Abstract

A uniform planar plasma is generated within a vacuum enclosure utilizing two planar radio frequency (RF) coils (31, 32) mounted adjacent to dielectric panels (25, 28) located on opposite sides of a working volume (34) within a vacuum enclosure. A gas is introduced into the vacuum enclosure, and RF power (45) is supplied to the two coils (31, 32) to induce an electric field within the working volume which provides a plasma within the working volume (34) which is substantially uniform laterally in a direction parallel to the coils (31, 32), and substantially symmetric across the working volume (34) between the coils (31, 32). The plasma in the working volume (34) can be used to treat a work piece (35), such as semiconductor substrates which require plasma treatment, and can further be used to treat simultaneously both surfaces of a substrate such as polymer films, metal sheeting and foils, and webs. The shape of the coils and the manner in which power is supplied to the coils can be selected to tailor the distribution of the RF induction fields to control the spatial distribution of the plasma within the vacuum enclosure.

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METHOD AND APPARATUS FOR PLANAR PLASMA PROCESSING

FIELD OF THE INVENTION

This invention pertains generally to the field of plasma processing of materials, and particularly to the generation of uniform planar low pressure plasmas for carrying out such processing.

BACKGROUND OF THE INVENTION

Plasma processing is used in the surface treatment of a variety of materials. For example, plasmas are used in semiconductor processing to clean or etch surfaces, and in deposition on the surfaces. Plasmas may also be used in cleaning a variety of materials, including metals, and in deposition of ions, free radicals, and other species from the plasma, either onto the surface of a material to provide surface coating, or into the bulk of the material. The use of plasmas in the treating of polymer surfaces has drawn increasing attention. See, e.g., G. Menges, et al., "Plasma Polymerisation -- Tailored Coats for Plastic Mouldings," Kunststoffe German Plastics, Vol. 78, No. 10, 1988, pp. 91-92; P. Plein, et al., "Plasmapolymerization as Coating Process for Plastic and Metallic Parts," Antec '88, 1988, pp. 1338-1341; R. Ludwig, "Plasmapolymerization -- A New Technology for Surface

Modification," Antec '89, 1989, pp. 915-917; J.T. Felts, et al., "Commercial Scale Application of Plasma Processing for Polymeric Substrates: From Laboratory to Production," presented at 38th Annual Symposium and Topical Conferences of the American Vacuum Society, Seattle, Washington, November 11-15, 1991 and published in J. Vac. Sci. and Technol., A10, p. 1675, 1992.

One approach to providing a relatively uniform plasma to the surface of a planar work piece involves the use of a planar radio frequency coil which is separated from the work piece (which is within a vacuum chamber) by a dielectric window. Application of radio frequency (RF) power, for example, at 450 kHz or 13.56 MHz, to the coil ionizes a gas within the vacuum chamber to create a plasma in a plane parallel to the planar coil. The planar plasma can be used to treat one surface of a work piece substrate such as a semiconductor wafer. Systems of this type are shown in United States patent 4,948,458 and published European Patent Application 89 480185.1, publication No. 0379828, published August 1, 1990. Such processes generally only allow treatment of one side of the substrate, and are not well suited to treating both sides of a substrate simultaneously. For example, plastic films may require treatment of both surfaces of the film, thus requiring a double treatment of the film. In addition, the induced electric field in the vacuum chamber from the excitation of the planar coil is not uniform over lateral dimensions parallel to the substrate, and rapidly decreases moving away from the coil in a direction normal to the plane of the coil. The consequent non-uniformity of the plasma limits the effective area of plasma treatment on the substrate.

SUMMARY OF THE INVENTION

In accordance with the present invention, a highly uniform planar plasma is generated which can be used to treat one or both sides of a work piece. The invention is not limited to the treatment of planar substrates, and can be used to treat work pieces having three dimensional geometries, such as cylinders and spheres, or complex geometries, such as lenses, or even re-entrant work pieces. The invention allows control of the field applied to the plasma in a working volume within the vacuum enclosure, which can be used to tailor the form of the plasma to best treat a particular work piece.

The apparatus of the invention has a vacuum chamber enclosure with two or more radio frequency (RF) coupling ports which are formed as parallel dielectric panels spaced from each other on either side of a space where the work piece is to be treated. A first planar radio frequency (RF) coil is mounted adjacent to the upper dielectric panel, and a second planar RF coil is mounted adjacent to the lower dielectric panel and parallel to the first coil to define a working volume in the vacuum chamber enclosure between the two coils. A gas to be ionized is fed into the vacuum chamber enclosure at several points selected to meet the needs of the treatment process. The RF induction coils are supplied with RF power at any desired RF frequency, with typical commercial RF heating frequencies including 450 KHz, 13.56 MHz, and 27.1 MHz. The RF power signal may be pulsed at lower audio frequencies to extend the stable power and pressure operating range of the plasma. The simultaneous excitation of the two coils extends the RF electric field to the workpiece within the chamber between the dielectric panels. As a consequence, highly uniform planar plasmas are formed within the chamber which can be used to treat the surfaces of both planar and complex work pieces.

The present invention is well suited to the treatment of large surface area substrate work pieces such as plastic or foil films. The film may be treated continuously by drawing the film from a roll through the plasma treatment area where the treatment is applied simultaneously to both sides of the film.

The coils may be formed in various geometries to best suit the particular application. For example, the coils are not limited to a circular form, but may be formed in other forms such as rectangular coils, the latter particularly suited to the treatment of elongated materials such as plastic films.

The planar coils may be driven by a single RF power supply, or may be driven independently by separate power supplies. Further, multiple coils, or separate current carrying elements within the coils, with appropriate connection of the RF power supply to such coils, can allow the distribution of the RF induction fields to be tailored to enhance or control the spatial distribution of the plasma, as desired, to obtain uniform processing of very large area substrates. Tailored fields can also be obtained, if desired, using a single coil having electrically separated turns which are separately supplied with RF power.

Further objects, features and advantages of the invention will be apparent from the following detailed description when taken in conjunction with the accompanying drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

In the drawings:

Fig. 1 is a perspective view, partially broken away, of a planar plasma processing apparatus in accordance with the invention.

Fig. 2 is a perspective view of a circular planar RF coil which may be utilized in the invention.

Fig. 3 is a perspective view of an alternative construction for a circular planar coil in accordance with the invention.

Fig. 4 is a cross-sectional view through a planar plasma processing apparatus of the invention which is adapted for the continuous processing of film fed from a roll of film.

Fig. 5 is an illustrative perspective view of a planar coil having a rectangular configuration which is especially suited for use in treating a large surface area of a film in the apparatus of Fig. 4.

Fig. 6 is a perspective view of an alternative embodiment of a rectangular coil which allows separate driving of each loop of the coil.

Fig. 7 is an illustrative view of the magnetic and electric field lines in planar plasma processing apparatus of the prior art which utilizes a single planar coil.

Fig. 8 is an illustrative view of the electric and magnetic field lines in the apparatus of the present invention.

Fig. 9 is a schematic circuit diagram of an exemplary RF plasma source power supply circuit for the apparatus of the present invention.

Fig. 10 is a simplified schematic for the circuit of Fig. 9.

Fig. 11 is a schematic circuit diagram of a circuit containing the planar coil of the present invention utilizing a reactive shunt across the coil.

Fig. 12 is a schematic circuit diagram of a circuit containing the planar coil of the present invention utilizing a reactance in series with the coil.

Fig. 13 is a schematic circuit diagram of the apparatus of the present invention with the two planar coils driven in parallel and utilizing a single impedance matching network.

Fig. 14 is a schematic circuit diagram of the apparatus of the present invention with the two planar coils driven in series and utilizing a single impedance matching network.

Fig. 15 is a schematic circuit diagram of the power supply circuit for the apparatus of the present invention with independent impedance matching for each coil and with driving from a single RF power source.

Fig. 16 is a schematic circuit diagram of a power supply system for the present invention having independent impedance matching for each coil, with each coil being driven by a separate RF power supply.

Fig. 17 is a perspective view of a Faraday shield mounted adjacent to an RF induction coil in accordance with the invention.

Fig. 18 is a plan view of an exemplary Faraday shield for use with a circular RF induction coil.

Fig. 19 is a plan view of an exemplary Faraday shield for use with a rectangular RF induction coil.

DETAILED DESCRIPTION OF THE INVENTION

With reference to the drawings, an apparatus for carrying out planar plasma processing in accordance with the present invention is shown generally at 20 in Fig. 1, with the apparatus being partially cut away to illustrate the interior. The apparatus 20 includes a vacuum chamber enclosure having a cylindrical sidewall 21, a top closure plate 22 and a bottom closure plate 23. In the exemplary apparatus 20, the enclosure which defines the vacuum chamber also includes a top dielectric panel 25 mounted to the top plate 22 to cover a central opening therein, and sealed to the plate 22 by a circular gasket 26. A bottom dielectric panel 28 is mounted to the bottom plate 23 to cover a central opening therein, and is sealed to the plate 23 by a gasket 29. The dielectric panels 25 and 28 are substantially flat and are mounted parallel to one another. Although the dielectric panels 25 and 28 comprise part of the walls forming the vacuum chamber enclosure in the embodiment of the apparatus 20, it is apparent that further enclosure walls may be formed to provide an evacuable enclosure around the panels 25 and 28, if desired.

A first planar coil 31 is mounted adjacent to the top dielectric panel 25, e.g., very close to or in contact with the outer face of the dielectric panel 25, and is wound in a substantially planar form with the plane of the coil 31 being substantially parallel to the plane of the panel 25. Similarly, a second planar coil 32 is mounted adjacent to, e.g., in contact with, the bottom dielectric panel 28. The coil 32 is wound in a substantially planar form, with the plane of the coil 32 being substantially parallel to the face of the dielectric panel 28. Thus, the first coil 31 and the second coil 32 are substantially parallel to each other and define between them, within the vacuum chamber enclosure, a working volume 34, at the center of which is mounted a work piece 35 which is to be plasma treated. The coils 31 and 32 are preferably formed to have their turns lying in a plane, but the coils of the present invention may deviate somewhat from perfectly planar coils without substantially affecting the formation of plasma within the working volume. As used herein, plasma treating or treatment includes all acts by which the work piece may be modified by the plasma, including implantation, deposition or coating from the plasma, and plasma etching, cleaning, and chemical surface modification. In the exemplary apparatus 20, the work piece 35 is supported by radial struts 37 which are mounted for support to the cylindrical vacuum chamber wall 21 and can have electrical connections therethrough to allow the workpiece to be electrically biased as required for the plasma treatment.

The gas to be ionized is fed through feed tubes 39 and 40 which extend through openings in the top dielectric plate 25 and the bottom dielectric plate 28, respectively. When RF power is supplied to the coils 31 and 32, in the manner as described further below, the feed gas 39 is ionized to generate a planar plasma within the working volume 34 which is centered at the position of the work piece 35. As also explained further below, the generation of the plasma within the working volume 34 is highly uniform over the surface of the work piece (or substrate) 35, and can be applied uniformly and simultaneously to both the top and bottom surfaces of the substrate 35. If desired, permanent magnets or electro-magnets can be mounted adjacent the enclosure walls of the vacuum chamber to provide magnetic confinement of the plasma in a conventional manner.

The vacuum chamber enclosure walls 21, 22 and 23 may be formed of conventional materials, e.g., aluminum or stainless steel, or ceramics, etc. with appropriate dielectric linings for the interior of the chamber, if desired. The dielectric panels 25 and 28 may be formed of conventional materials such as quartz, ceramics or glass. The vacuum chamber may be evacuated with conventional pumps, attached to vacuum ports (not shown in Fig. 1) in one or more of the walls of the vacuum chamber enclosure, to evacuate the chamber to the desired pressure level.

The processing apparatus of the present invention is capable of operating over a wide range of partial vacuum pressures within the vacuum chamber, for example from 0.5 milliTorr to 50 Torr or higher. The first coil 31 is attached by conducting lines 44 to an RF power supply 45 which can include an impedance matching network(s) as described further below, and the second coil 32 is similarly connected by conducting lines 46 to the RF power supply 45. The RF power supply 45 provides drive power to both coils at a desired RF frequency, which may be typical RF commercial heating frequencies, e.g., 450 KHz, 13.56 MHz, and 27.1 MHz. The RF input power may be pulsed at lower frequencies, e.g., audio frequencies, to extend the stable power and pressure operating range of the plasma source.

The large RF currents, (e.g., 10 to 70 amperes) circulating in the coils 31 and 32 drive strong RF electromagnetic fields (typically greater than 100 volts per meter electric fields) within the working volume 34. These fields drive circulating currents in the gas within the working volume, which heats the plasma. The use of the two coils 31 and 32, parallel to one another on opposite sides of the working volume 34, provides a uniform planar plasma within the working volume at the position of the substrate 35 which enables a uniformity of surface treatment to be obtained which has not been heretofore possible. Moreover, in the systems of the prior art using a single planar coil, only one surface of a substrate could be treated, and the form of the substrate or work piece is generally limited to relatively small planar substrates such as semiconductor wafers. The utilization of the two or more coils such as the coils 31 and 32 provides uniform fields within the working volume which produce a uniform plasma which allows treatment of multiple surfaces of materials.

A perspective view of an exemplary planar coil for use in the invention, such as the coil 31 or 32 of Fig. 1, is shown in Fig. 2. The coil of Fig. 2 is formed of a single continuous conductor, which may be conventional electrical conductors such as copper, aluminum, etc., having several turns 50 which are coplanar with one another. The turns may be formed as shown in Fig. 2, being substantially circular, with short stub conductors 51 connecting the end of each turn except the innermost to the next inner turn.

Alternatively, the coil 31 or 32 may be formed as illustrated in Fig. 3, having several separated turns 53, each a fully circular form, in which independently controllable currents flow in each of the turns 53. Specifically, a separate electrical connection through multiple lines 44 or 46 (depending on whether the coil is the upper coil 31 or lower coil 32) can be made to the free ends of each of the turns 53 through which RF power can be supplied to each turn from the power supply system 45, with the current flowing in each of the turns adjusted as desired to allow a tailoring of the electric and magnetic fields from each turn. In utilizing such a coil, the RF power supply system 45 may have separate conducting lines 44 or 46 extending to each of the turns 53, with separate power supplies and/or independent adjustment of RF phase or of reactances in series or parallel with each turn of the coil. If desired, such a coil having separate turns which are separately supplied with RF power may be used alone to produce tailored fields and a plasma tailored to a particular workpiece.

A cross-sectional view through a modified embodiment of the apparatus suited for the treatment of work pieces comprising continuous films of material such as polymers, metal sheeting and foils, and webs, is shown in Fig. 4. The planar processing apparatus may be substantially the same as shown in Fig. 1 with appropriate modifications to the geometry if desired, e.g., by making the enclosure walls 21 of the vacuum chamber rectangular rather than circular, and by having rectangular rather than circular upper and lower dielectric panels 25 and 28, respectively. In addition, the coils 31 and 32 may be formed in rectangular rather than circular shapes, as described below. In particular, the apparatus of Fig. 4 is modified by having an inlet port 55 formed at one position along the side wall 21 of the vacuum enclosure which extends into an unwind vacuum chamber defined by walls 56 within which is situated a roll 57 of film 58 to be treated. The film 58 is unwound from the roll 57, passed over tensioning rollers 59 and through a vacuum feed-through mechanism 60 and the port 55 into the working volume 34 of the plasma processing apparatus. The vacuum feed-through mechanism or material transfer aperture 60 helps to minimize the passage of gas from the working volume into the unwind vacuum chamber, or the passage of gases from the vacuum chamber into the working volume. After treatment of the film 58 within the working volume

34, the film is continuously drawn to an exit port 62 formed in the sidewall 21 of the vacuum enclosure opposite to the entrance port 55, and thence through a vacuum feed-through mechanism 63 into a rewind vacuum chamber defined by enclosure walls 64 where the film 58 is wound over tensioning rollers 65 onto a rewind roll 66. Outlet ducts 67 and 68 are connected to conventional vacuum processing pumps (not shown) to maintain the desired low pressure level within the working volume. Additional gas feed supply lines 70 are preferably provided on the top plate 22, and additional supply lines 71 are connected through the bottom plate 23, to supply sufficient amounts of the feed gas to the working volume in supplement to the feed gas supplied through the inlets 39 and 40.

Because the coils 31 and 32, when driven by the RF power supply 45, provide a uniform plasma on both sides of the continuous film 58 within the working volume 34, both surfaces of the film may be treated with the plasma simultaneously and in a continuous process in which the roll 57 is continuously unwound and the roll 66 is continually wound up.

An exemplary planar coil which may be used either as the first coil 31 or the second coil 32 in the apparatus of Fig. 4 is shown in Fig. 5. The coil of Fig. 5 is formed of a continuous conductor having rectangular turns 72 which lie substantially in a plane. The long sections of each rectangular turn 72 may be oriented perpendicular to the direction of travel of the film 58 to cause a plasma to be developed within the working volume 34 which extends over the entire width of the film. Because of the arrangement in the present invention of the two planar coils 31 and 32 on both sides of the working volume 34, a substantially uniform planar plasma is formed within the working volume even though each turn 72 deviates substantially from a circular form.

Fig. 6 is a perspective view of a variation of a rectangular planar coil in which the turns 73 are formed of conductors which are separate from one another, allowing independently controllable currents to be passed from conducting lines 44 or 46 through each of the turns 73 to thereby allow the fields produced by the turns to be adjusted.

It is a particular advantage of the present invention that strong and uniform RF electric fields are developed essentially throughout the working volume. Such uniform fields are not generally obtainable with previously existing planar processing apparatus which utilized a single planar coil. The fields seen in such prior art systems are illustrated in Fig. 7. Such prior art systems utilize a single coil 90 mounted above a dielectric plate 91. For purposes of illustration, magnetic field lines are indicated at 93, and electric field lines are illustrated at 94 (which are 90° to the magnetic field lines), the electric field lines being illustratively shown extending into or coming out of the paper. For purposes of illustration, current flowing in the turns 90 into the plane of the paper is illustrated by "x", current flowing out of the paper by "•", and with the direction of the electric field into the paper illustrated by "x" and electric field directed out of the plane of the paper illustrated by "o". A graph 95 illustrates the induced electric field intensity as a function of the distance away from the dielectric plate 91 in the "z" direction normal to the coil 90. As illustrated in Fig. 7, the magnetic field lines 93 typically extend only a short distance below the dielectric plate 91, and the electric field intensity, as illustrated by the graph 95, typically drops off rapidly with increasing distance from the dielectric plate 91. It is known that electron heating and power absorption occurs most strongly at the regions of strongest induced RF electric fields, and that the spatial distribution of the RF electron heating regions and discharge boundaries will influence the spatial uniformity of gas discharge properties (i.e., plasma potential and electron density).

Consequently, in the prior art system as illustrated in Fig. 7, the plasma will generally not be spatially uniform in either the lateral direction parallel to the plane of the coil 90, or in the Z direction perpendicular to that plane, and the non-symmetrical characteristics in the Z direction of the electric field generating the plasma, as illustrated by the graph 95, allow only a single side of a work piece to be plasma treated.

The fields in the apparatus of the present invention are illustratively shown in Fig. 8. It is seen that the magnetic field lines 96 extend between the dielectric panels 25 and 28 and that the electric field induced by the RF magnetic field, illustrated at 97 in Fig. 8, is distributed throughout the working volume 34 of the apparatus. The electric field intensity in the Z direction (a direction normal to the plane of the coils 31 and 32) between the panels 25 and 28 is illustrated by the graph 98 in Fig. 8, and is seen to be a symmetric field in the Z direction, resulting in a symmetrical production of plasma in the Z direction through the working volume which may be applied to both sides of a work piece which is immersed in the plasma. By selectively arranging the position of the coils 31 and 32 or the turns within the coils, the spatial distribution of the induced RF plasma heating electric fields may be shaped as desired, particularly to improve the uniformity of the discharge properties as required for the intended workpiece treatment. These treatments may include plasma assisted etching, deposition, ion implantation processes, and the like. The shape of the coils 31 and 32 can be used to tailor the radial (parallel to the coils) distribution of the electromagnetic fields. Such coil arrangements do not need to be geometrically symmetric, and they do not necessarily need to be symmetrically driven by the RF power supply system.

It is understood that Figs. 7 and 8 are simplified views for purposes of illustration. Only the electric and magnetic fields that are induced by the RF currents on the coils 31 and 32 are shown. Although the coils can sustain high RF voltages, and the quasi-static electric fields introduced by these voltages can capacitively couple RF power to the plasma in the working volume 34, these electric fields are not shown in Figs. 7 and 8 for purposes of simplicity. If desired, Faraday shields of conventional design can be mounted between the coils 31 and 32 and the working volume to restrict the degree to which the capacitive electric fields heat the plasma in the working volume 34. An exemplary conventional Faraday shield which may be used is shown at 110 in Fig. 17 positioned adjacent to the induction coil 31 or 32, and a plan view of the exemplary shield 110 is shown in Fig. 18. Faraday shields 110 may generally be mounted between the coils 31 and 32 and the adjacent dielectric panels 25 and 28. The shields may be made from various conducting materials, such as copper and aluminum, and may conveniently be cut or stamped from thin metal sheets. The shield 110 has an outer conductive ring 112 and inwardly projecting spokes 113. Each shield 110 is electrically grounded, and preferably each is split by an opening 114 in the outer ring 112 to reduce the induction of eddy currents in the shield. The size and spacing of the spokes 113 may be selected to provide the requisite shielding for a coil 31 or 32 of a particular size. For rectangular coils, a rectangular shield 120 as shown in Fig. 19 may be used. The shield 120 has two separated sections 121, each comprising a conductive strip 123 and fingers 124 which project therefrom. Of course, other Faraday shield configurations may be used to suit other coil configurations.

A schematic circuit diagram of a lumped parameter circuit representation of the RF power supply 45 including impedance matching network(s), and one of the coils 31 and 32 inductively coupled to the plasma in the working volume, is illustrated in Fig. 9. The power supply includes an RF power source 100 having a source impedance Z_s. A transmission line with electrical impedance Z_t (typically a 50 ohm coaxial cable) conveys the power from the power source 100 to the power coupling system of the apparatus. The single coil 31 or 32 has an inductance L_c, and the conductive discharge is represented by an inductance L_p and a resistance R_p. The value of the coupling coefficient, K, between L_c and L_p depends on the design of the coil, the discharge operating conditions, the selection of materials of the apparatus, and the distances which separate the coil from the discharge. The transformer model for the coil and discharge can be transformed into the equivalent circuit shown in Fig. 10 which has an effective inductance L_{eff} and an effective resistance R_{eff}, with the ideal voltage source 100 and its impedance Z_s shown lumped together as a source 101. The power supply can include compensation network capacitors C_1 and C_2 which serve to step up the voltage from the power supply to drive a strong RF current across L_c and to transform the effective impedance of the power coupling system to match that of the power supply and transmission line impedance. Typically, the values of C_2 and L_{eff} are adjusted so that the circuit is near resonance at the RF driving frequency in order to drive the largest possible current for a given power supply voltage. Specifically, C_2 is selected such that:

$$C_2 \approx 1/(\omega^2 L_{eff}),$$

where ω is the RF driving frequency. The system of capacitors C_1 and C_2 forms an impedance matching network between the power source and the coils. Automated impedance matching networks are commercially available from several manufacturers.

In the present invention, the multiple planar coils can be driven together or separately, and the power coupling property of each induction element (turn) of the coil system, or of each complete coil system, can be adjusted by combining selected coil elements or coil systems with an additional reactive (inductive) element which plays no direct role in plasma heating. Fig. 11

illustrates a coil element, or coil system, placed in parallel with an inductive impedance represented as jX. Fig. 12 shows an alternative implementation in which the inductive impedance represented as jX is connected in series with the coil element. Such parallel or series inductance may be used to preferentially restrict or enhance the current distribution and induction fields associated with any particular coil element or coil system without requiring physical reconstruction of the coil element or coil system. In either of the arrangements of Fig. 11 or Fig. 12, for purposes of the following illustrations, the effective inductances of the entire system, including the additional reactive element, may be considered to have an effective inductance L_{eff} and an effective resistance R_{eff}. For purposes of the following illustrations, mutual induction effects in the lumped circuit parameter models have been excluded. Such mutual inductance effects will occur between closely spaced coil elements and coil systems.

Fig. 13 is a lumped parameter circuit representation of an RF power supply having an RF power source 101 with two coil elements connected in parallel. Fig. 14 is a lumped parameter circuit representation of the RF power supply with two coil elements connected in series. In certain situations, it may be difficult to drive both coils with the same impedance matching network or with the same RF power supply. The schematic diagram of Fig. 15 illustrates the manner in which a power divider 102 and optional phase shifters 103 may be incorporated in a power distribution system used to drive a dual coil plasma processing source with independent impedance matching networks. The phase shifters 103 receive power from two outputs 104 of the divider, and allow selection of the phase of the power applied to the two coils. The phase shifters 103 are used to control the possibility of constructive and destructive interference of the induced fields from each coil, and also allow control of the spatial distribution of RF power absorption and electron heating. A circuit diagram of an analogous system for driving a dual coil plasma source with separate power supplies is shown in Fig. 16. In this case, the separate power supplies include RF power sources 106 and 107 which are each connected to receive a signal from a phase reference generator 108 to control the phase difference of the power supplied to the two coil systems.

Commercially available power supplies can be utilized to drive the planar coils of the present invention. Examples of suitable components are those available from RF Power Products, Inc. of Marlton, New Jersey, including RF power generators in the RFx series, which operate at 13.56, 27.12 or 40.68 MHz, RF impedance matching networks in the AMx and AMN-x001E series, and common exciters (phase reference signal generators) in the CEX-x series. Other suppliers of RF power systems and impedance matching systems are Electronic Navigation Industries of Rochester, New York, which produces power supplies and amplifiers for plasma systems, and RF Services, Inc., which produces computerized RF automatic matching networks for plasma systems.

Although two planar coils have been shown for purposes of illustration, it is understood that additional coils may also be utilized, for example, by providing several pairs of spaced coils extending in sequence along the path of a continuous film being treated so as to provide adequate treatment of the surfaces of the film at a maximized production rate, or pairs of coils and additional single coils, or separately powered turns of a single coil.

It is understood that the invention is not confined to the illustrative embodiments described herein, but embraces all such modified forms thereof as come within the scope of the following claims.

CLAIMS

What is claimed is:

1. Planar plasma processing apparatus comprising:

(a) an enclosure having walls defining a vacuum chamber, and upper and lower planar dielectric panels arranged parallel to and spaced from one another across the vacuum chamber;

(b) a first electrically conductive substantially planar radio frequency coil mounted adjacent to the upper dielectric panel;

(c) a second electrically conductive substantially planar radio frequency coil mounted adjacent to the lower dielectric panel and parallel to the first coil to define a working volume between them within the vacuum chamber;

(d) means for supporting a workpiece having top and bottom surfaces within the working volume; and

(e) a radio frequency power supply connected to provide radio frequency electrical power to the first and second coils to induce an electric field throughout the working volume to excite a plasma in a gas that may be introduced into the working volume at both the top and bottom surfaces of the workpiece simultaneously, the electric field from the coils and the plasma induced thereby being substantially uniform at both the top and bottom surfaces of the workpiece.

2. The apparatus of Claim 1 wherein each of the planar coils is formed of a continuous conductor having substantially circular turns which lie in substantially the same plane.

3. The apparatus of Claim 1 wherein each of the planar coils has substantially circular turns which are electrically separated from one another and which are arranged to lie in substantially the same plane.

4. The apparatus of Claim 3 wherein the power supply is connected to provide power separately to each of the coil turns.

5. The apparatus of Claim 1 wherein each of the planar coils is formed of a continuous conductor having turns which are substantially rectangular and which lie in substantially the same plane.

6. The apparatus of Claim 1 wherein each of the planar coils has substantially rectangular turns which are electrically separated from one another and which are arranged to lie substantially in the same plane.

7. The apparatus of Claim 6 wherein the power supply is connected to supply power separately to each of the turns.

8. The apparatus of Claim 1 wherein the power supply includes two separate RF power supplies which provide RF power to the first and second coils separately.

9. The apparatus of Claim 8 further including a phase reference signal generator providing a phase reference signal to the two RF power supplies.

10. The apparatus of Claim 1 wherein the first and second coils are electrically connected together in series and the radio frequency power supply provides power to the series connected coils.

11. The apparatus of Claim 10 including a impedance compensation network connected between the RF power supply and the series connected coils.

12. The apparatus of Claim 1 wherein the first and second coils are electrically connected together in parallel and wherein the radio frequency power supply provides power to the coils in parallel with one another.

13. The apparatus of Claim 12 including a impedance compensation network connected between the radio frequency power supply and the parallel connected coils.

14. The apparatus of Claim 1 wherein the radio frequency power supply includes an RF power source, a power divider receiving power from the RF power source and providing power at two outputs, and a phase shifter connected between each output of the divider and one of the coils to allow selection of the phase of the power provided to each coil.

15. The apparatus of Claim 1 wherein the workpiece is a film material and the means for supporting the workpiece includes an unwind vacuum enclosure for an unwind reel of film joined to the vacuum chamber enclosure to allow passage of the film from an unwind reel into the working volume, and a rewind vacuum enclosure for a rewind reel for the film which is joined to the vacuum chamber enclosure to allow passage of the film from the working volume onto a rewind reel, and further including gas inlet ports into the vacuum chamber enclosure to allow introduction of gas for generation of the plasma in the working volume.

16. The apparatus of Claim 15 wherein each of the planar coils is formed of a continuous conductor having

turns which are substantially rectangular and which lie in substantially the same plane.

17. The apparatus of Claim 15 wherein each planar coil has substantially rectangular turns which are electrically separated from one another and which are arranged to lie substantially in the same plane.

18. The apparatus of Claim 1 including a Faraday shield mounted between each coil and the working volume.

19. A method for forming a plasma in a working volume within a vacuum enclosure, comprising the steps of:

(a) providing a first substantially planar coil adjacent to a dielectric panel on one side of the working volume within the vacuum enclosure;

(b) providing a second substantially planar coil adjacent to a dielectric panel on the side of the working volume opposite to the first coil;

(c) supporting a workpiece having top and bottom surfaces within the working volume;

(d) introducing a selected gas into the vacuum enclosure and into the working volume; and

(e) providing radio frequency power to both coils to induce a radio frequency electric field in the working volume to excite the gas in the working volume to produce a plasma therein at both the top and bottom surfaces of the workpiece simultaneously, the electric field from the coils and the plasma induced thereby being substantially uniform at both the top and bottom surfaces of the workpiece.

20. The method of Claim 19 wherein in the step of applying radio frequency power, the power is provided to both coils at the same frequency.

21. The method of Claim 20 wherein in the step of providing radio frequency power, power is provided at different phases to each coil.

22. The method of Claim 19 wherein in the step of providing radio frequency power to the coils, power is supplied to the two coils connected in series.

23. The method of Claim 19 wherein in the step of providing radio frequency power to the coils, power is provided to the two coils connected in parallel.

24. The method of Claim 19 wherein the step of providing radio frequency power to the coils is carried out by providing power from a separate RF power source to each coil.

25. The method of Claim 24 including the step of providing a phase reference signal to each of the power sources providing power to the two coils to maintain a selected phase difference between the power from the two power sources.

26. The method of Claim 19 wherein at least one of the first and second coils is formed of turns which are electrically separated from one another, and wherein the step of providing power includes the steps of providing radio frequency power separately to each turn of at least one of the first and second coils which has turns electrically separated from one another.

27. Planar plasma processing apparatus comprising:

(a) an enclosure having walls defining a vacuum chamber and a dielectric panel adjacent to a working volume in the vacuum chamber;

(b) an electrically conductive substantially planar radio frequency coil mounted adjacent to the dielectric panel and separated by the panel from the working volume, the coil formed of turns which are electrically separated from one another;

(c) a radio frequency power supply connected to provide radio frequency electrical power separately to each of the turns of the coil to induce an electric field in the working volume to excite a plasma in a gas that may be introduced into the working volume.

28. The apparatus of Claim 27 wherein the planar coil has substantially circular turns which are electrically separated from one another and which are arranged to lie in substantially the same plane.

29. The apparatus of Claim 27 wherein the planar coil has substantially rectangular turns which are electrically separated from one another and which are arranged to lie substantially in the same plane.

30. A method of treating a workpiece with a plasma in a working volume within a vacuum enclosure, comprising the steps of:

(a) providing a substantially planar coil adjacent to a dielectric panel on one side of the working volume within the vacuum enclosure, the coil formed of turns which are electrically separated from one another,

(b) introducing a selected gas into the vacuum enclosure and into the working volume; and

(c) providing radio frequency power separately to each turn of the coil to induce a radio frequency electric field in the working volume to excite the gas in the working volume and produce a plasma therein.

31. The method of Claim 30 including the step of treating a workpiece in the working volume with the plasma produced therein.

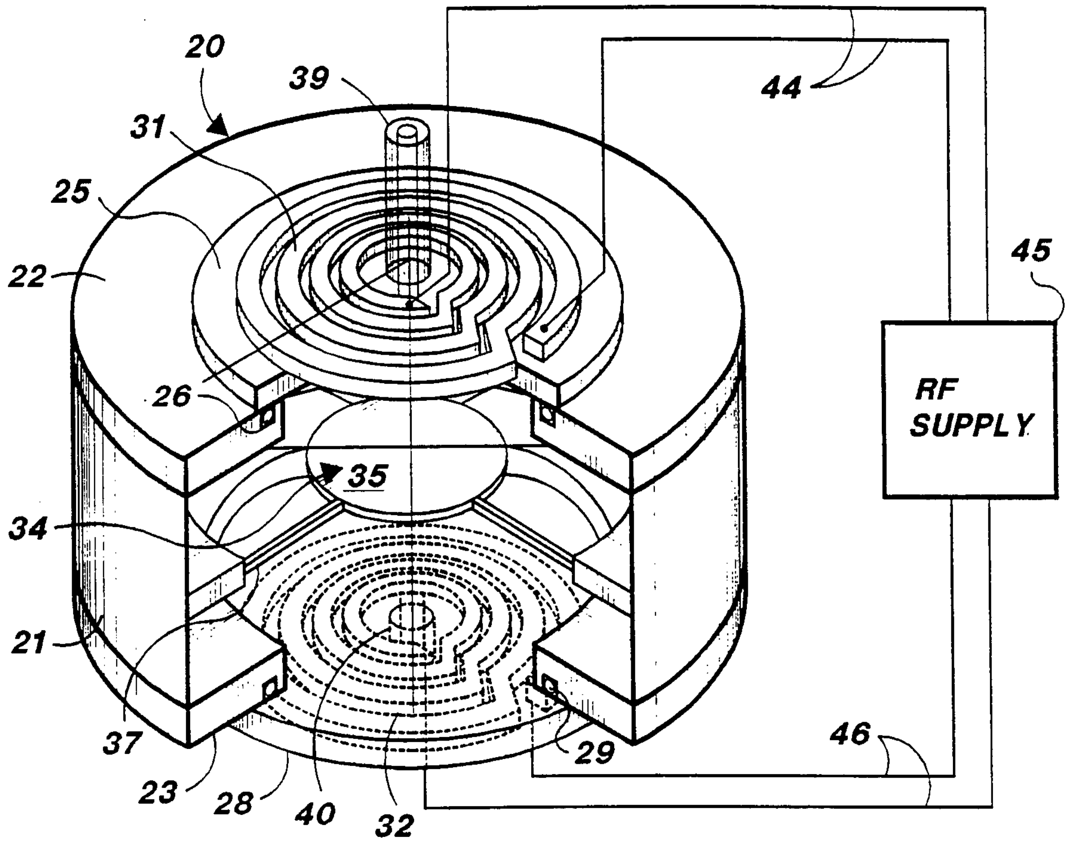


FIG. 1

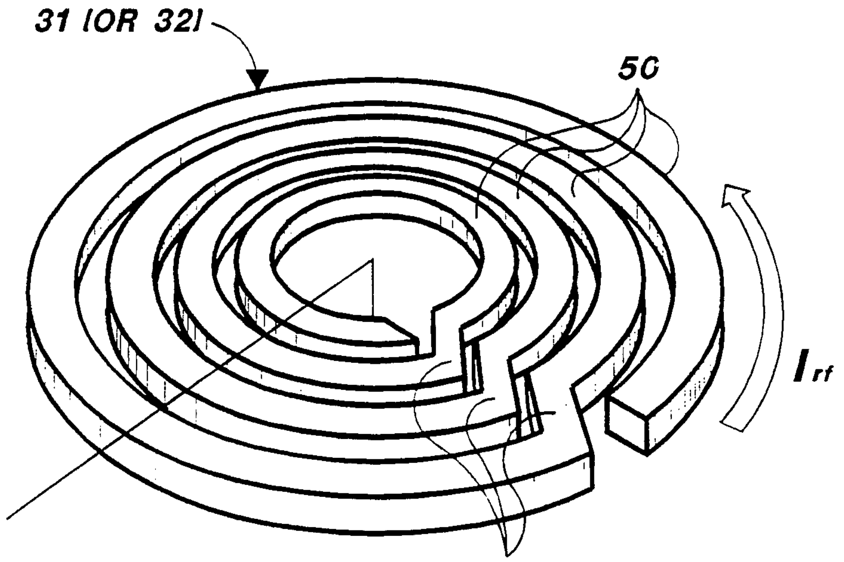
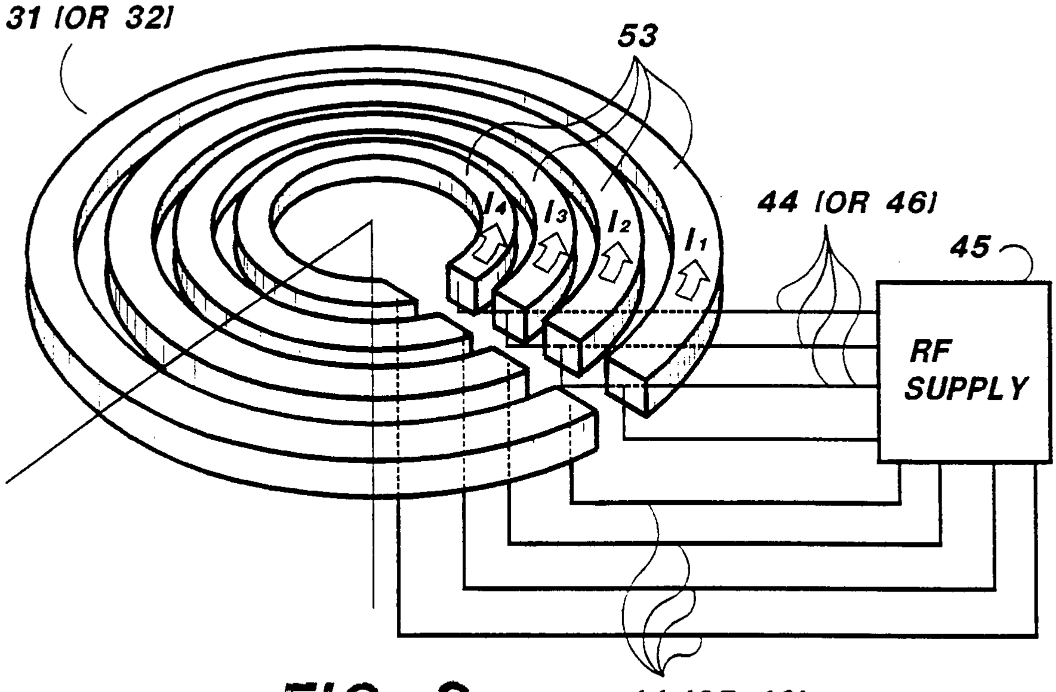

31 (OR 32)
50
I_{rf}
51

FIG. 2


31 (OR 32)
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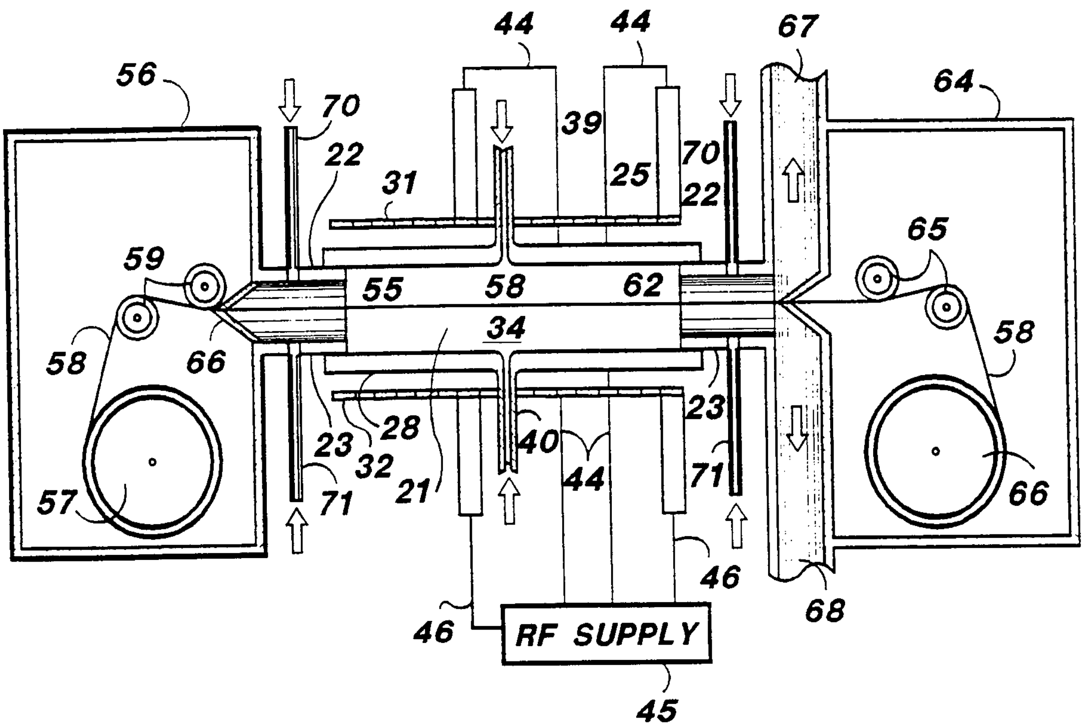
I_4
I_3
I_2
I_1
44 (OR 46)
45
RF SUPPLY
44 (OR 46)

FIG. 3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44
67
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22
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25
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65
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62
34
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58
66
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32
44
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71
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66
46
46
68
RF SUPPLY
45

FIG. 4

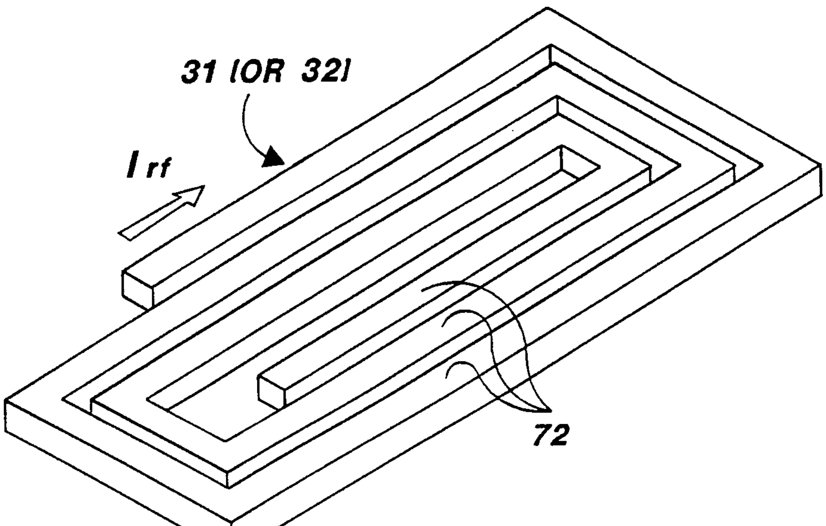
31 (OR 32)
I rf
72

FIG. 5

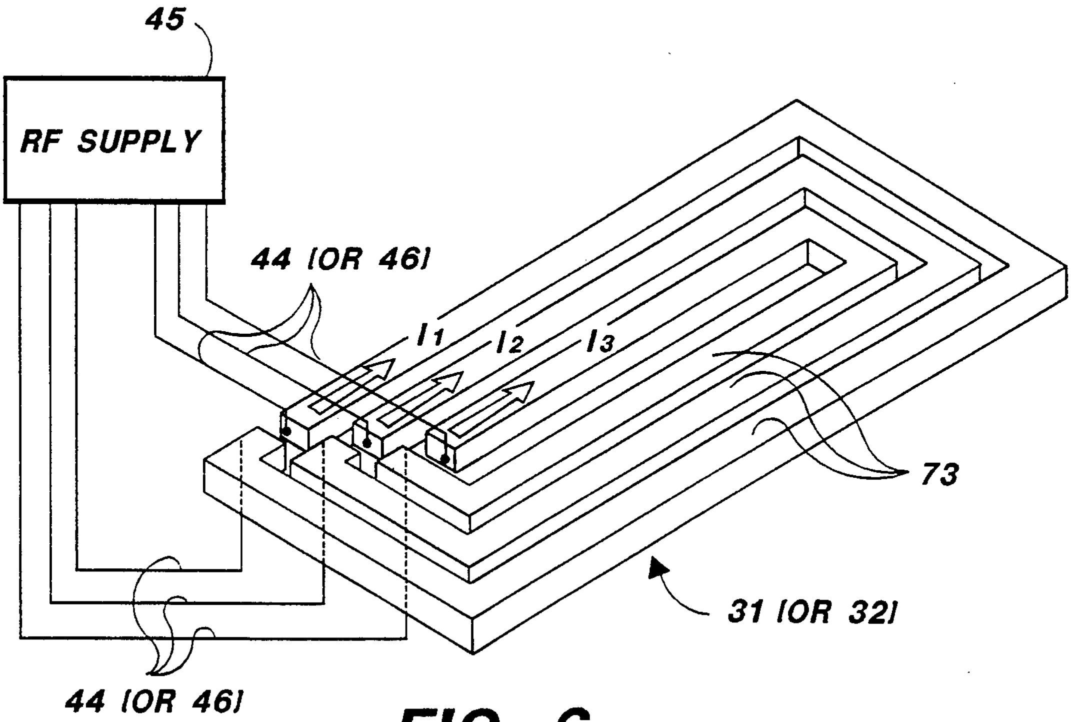

FIG. 6

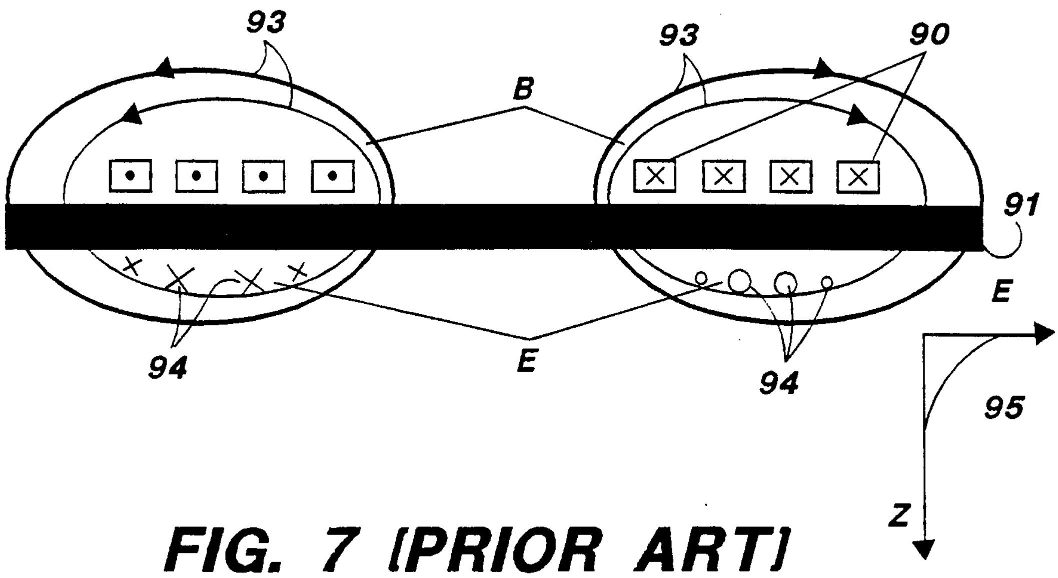

FIG. 7 [PRIOR ART]

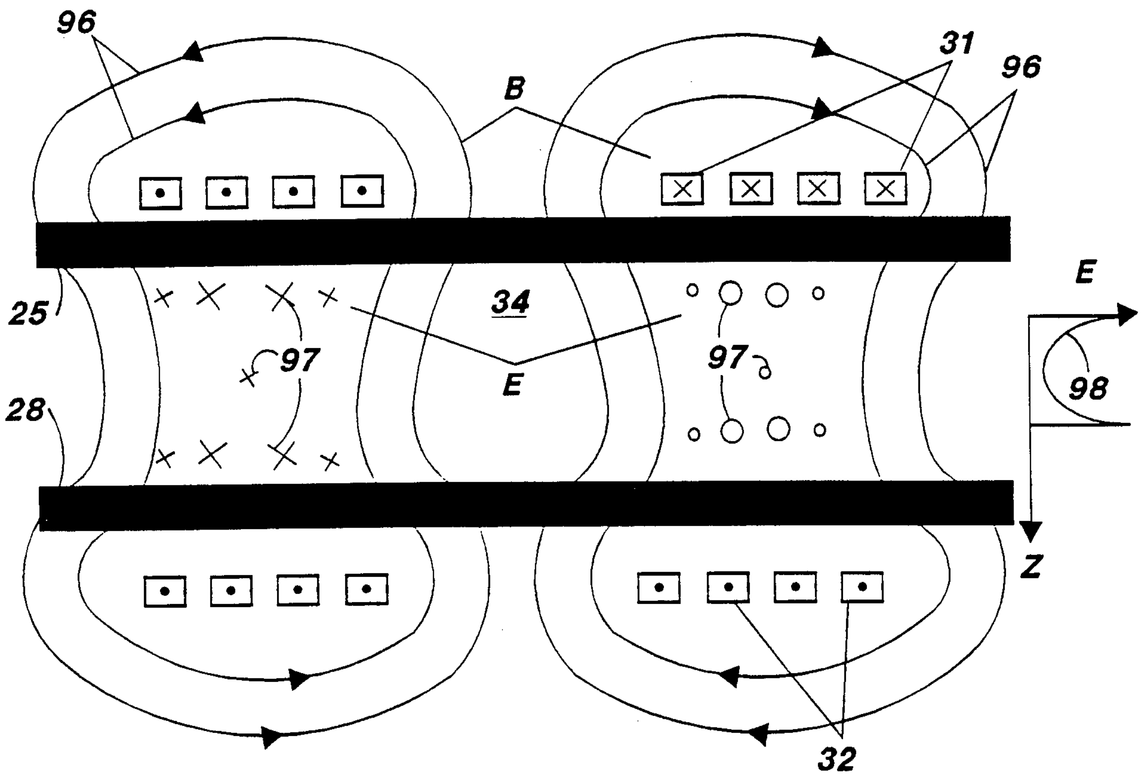

FIG. 8

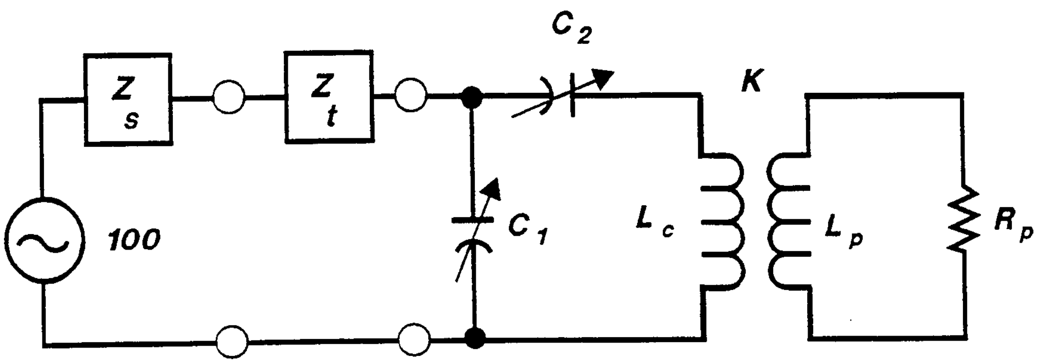

FIG. 9

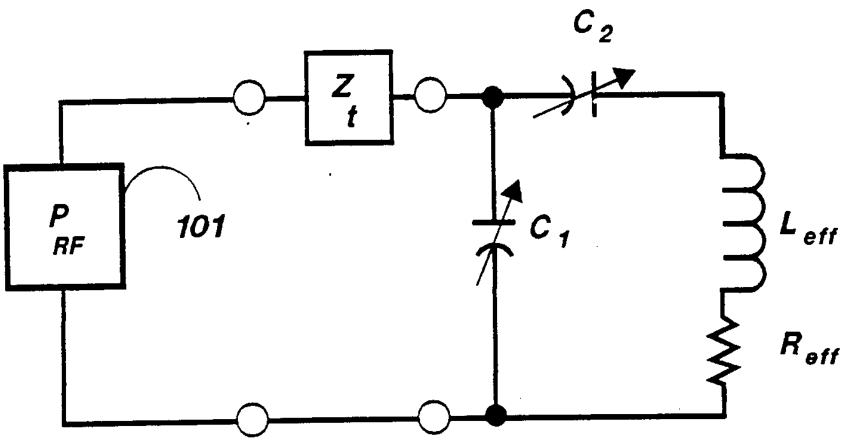

FIG. 10

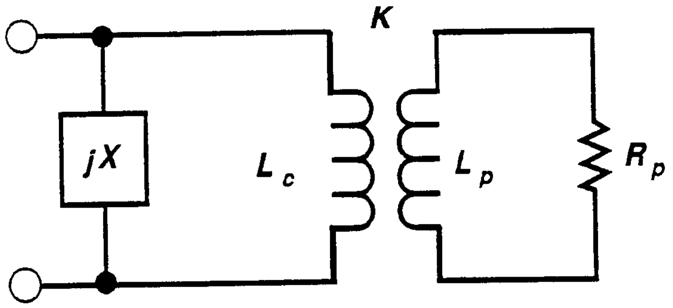

FIG. 11

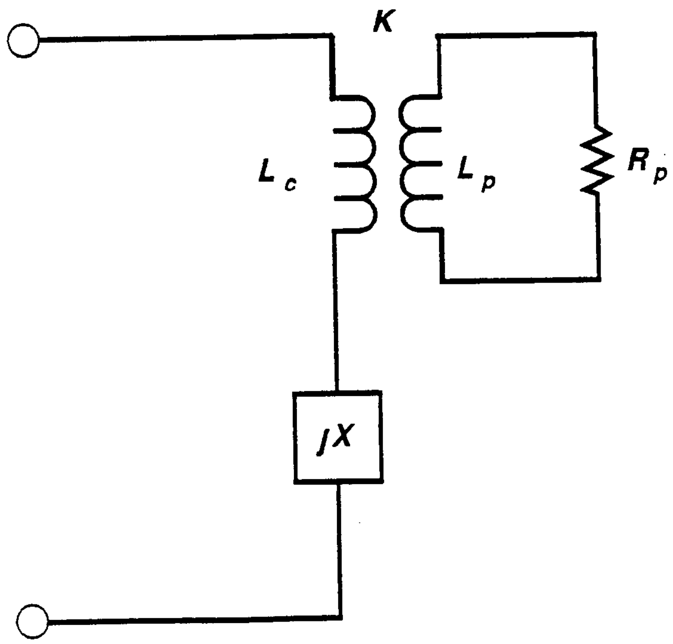

FIG. 12

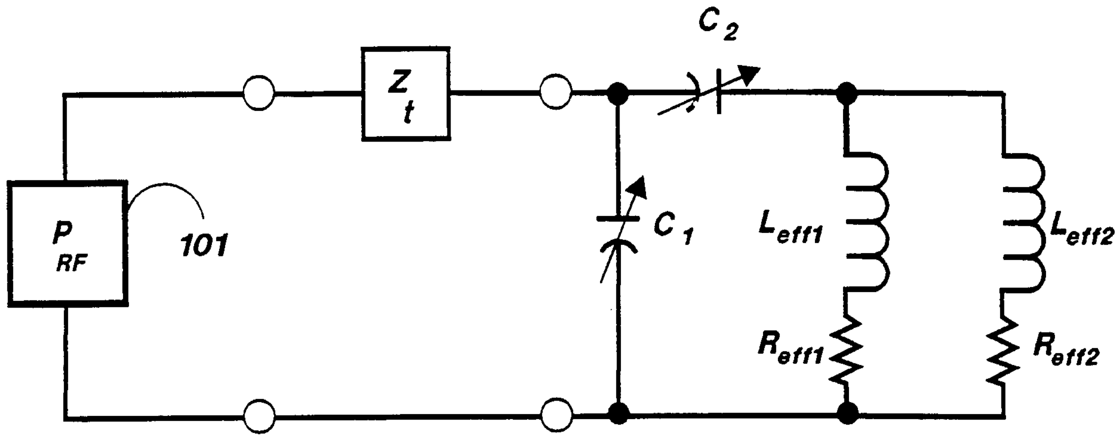
C2
Zt
P RF
101
C1
Leff1
Leff2
Reff1
Reff2

FIG. 13

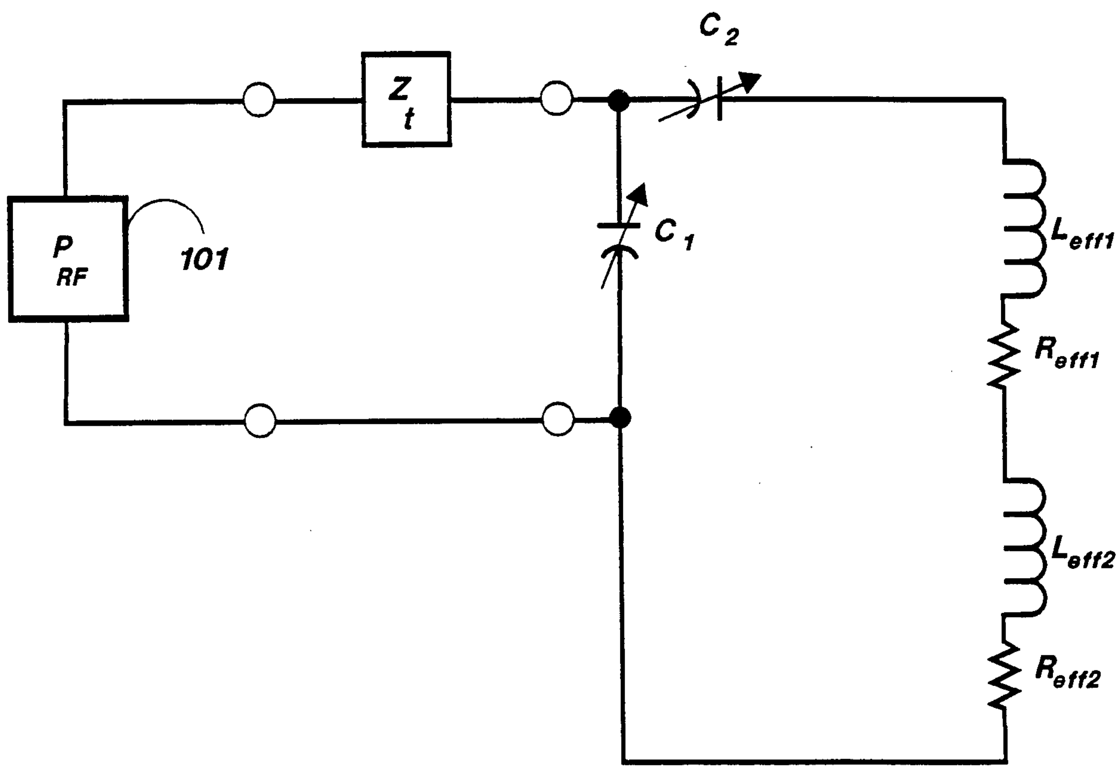
C2
Zt
P RF
101
C1
Leff1
Reff1
Leff2
Reff2

FIG. 14

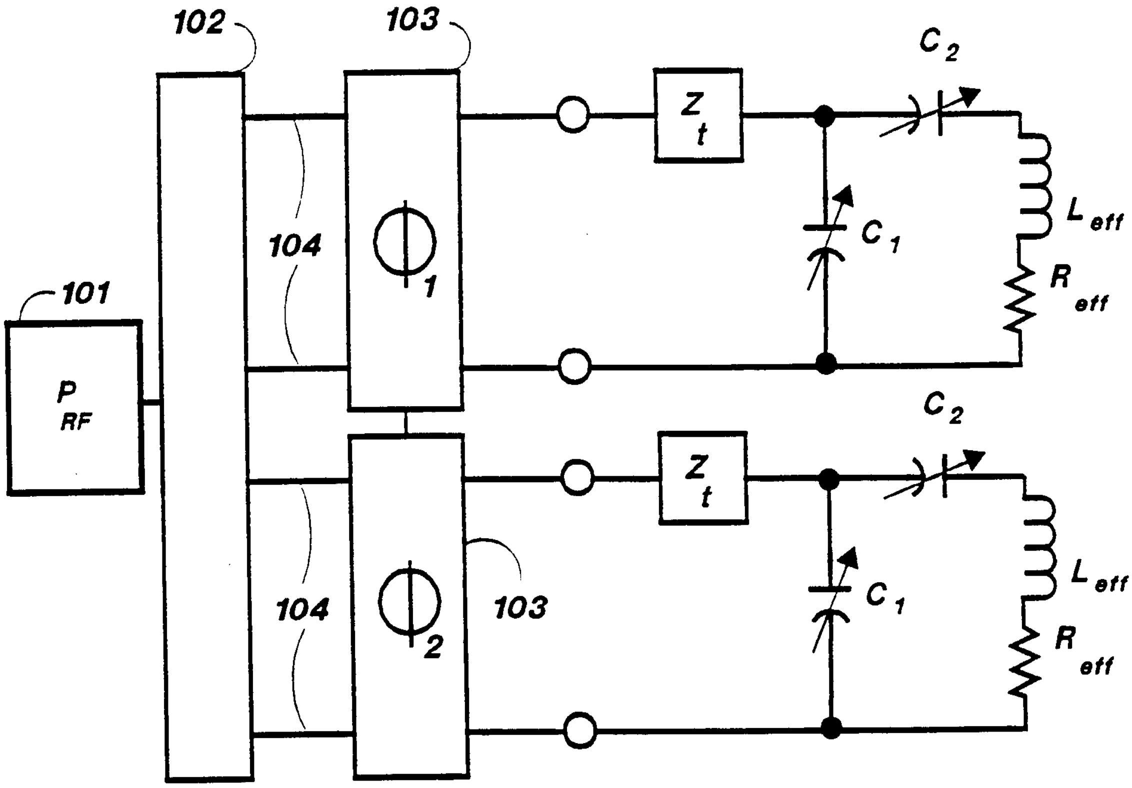
102
103
C_2
Z_t
L_{eff}
104
C_1
101
R_{eff}
P_{RF}
C_2
Z_t
L_{eff}
104
103
C_1
R_{eff}

FIG. 15

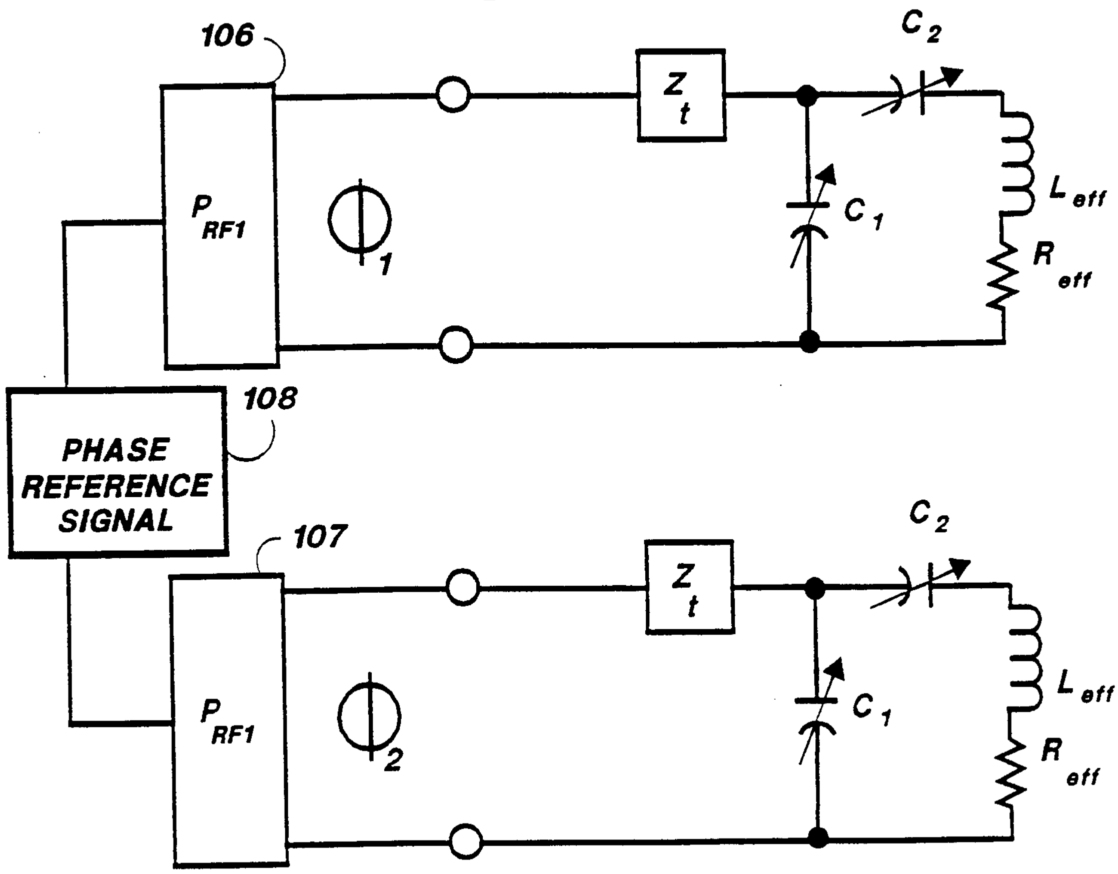
106
C_2
Z_t
P_{RF1}
L_{eff}
C_1
R_{eff}
108
PHASE
REFERENCE
SIGNAL
107
C_2
Z_t
L_{eff}
P_{RF1}
C_1
R_{eff}

FIG. 16

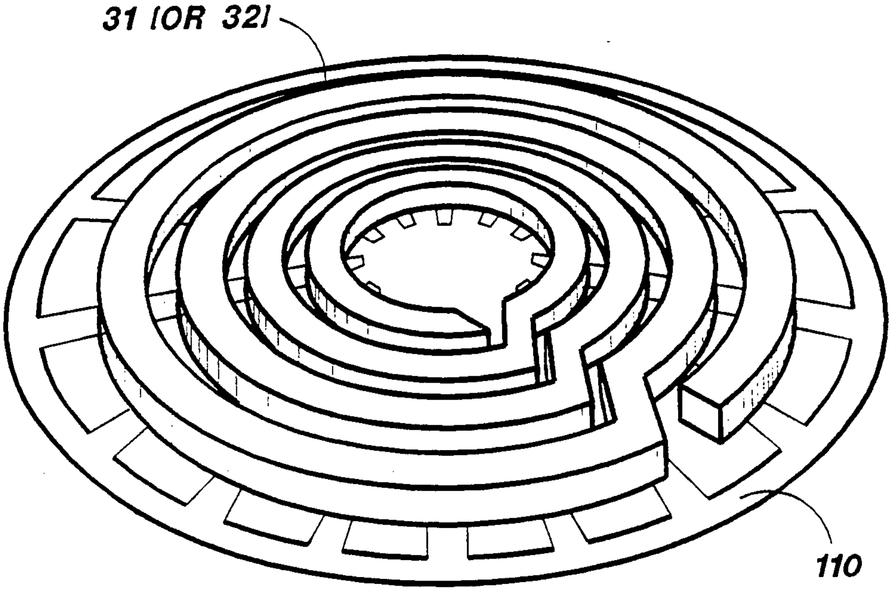

FIG. 17

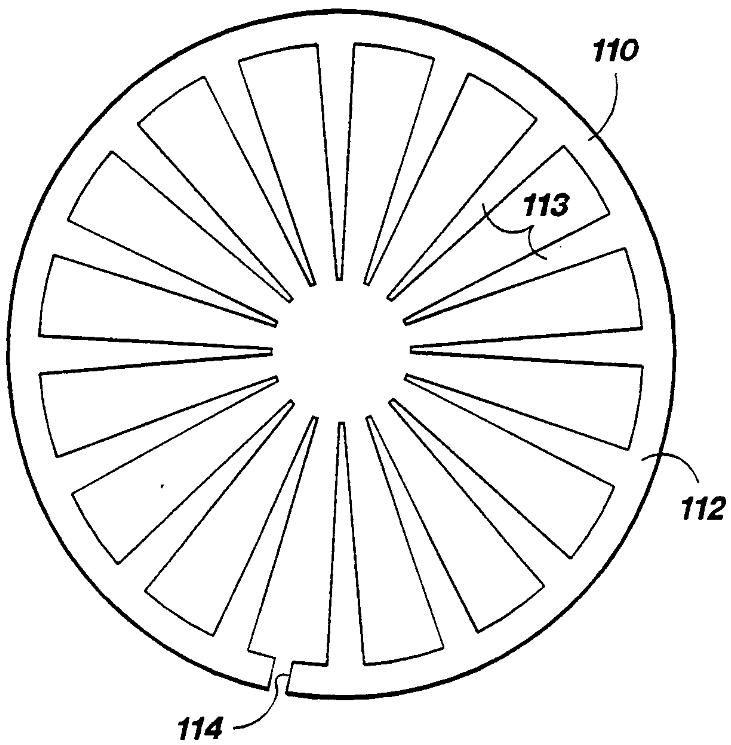

FIG. 18

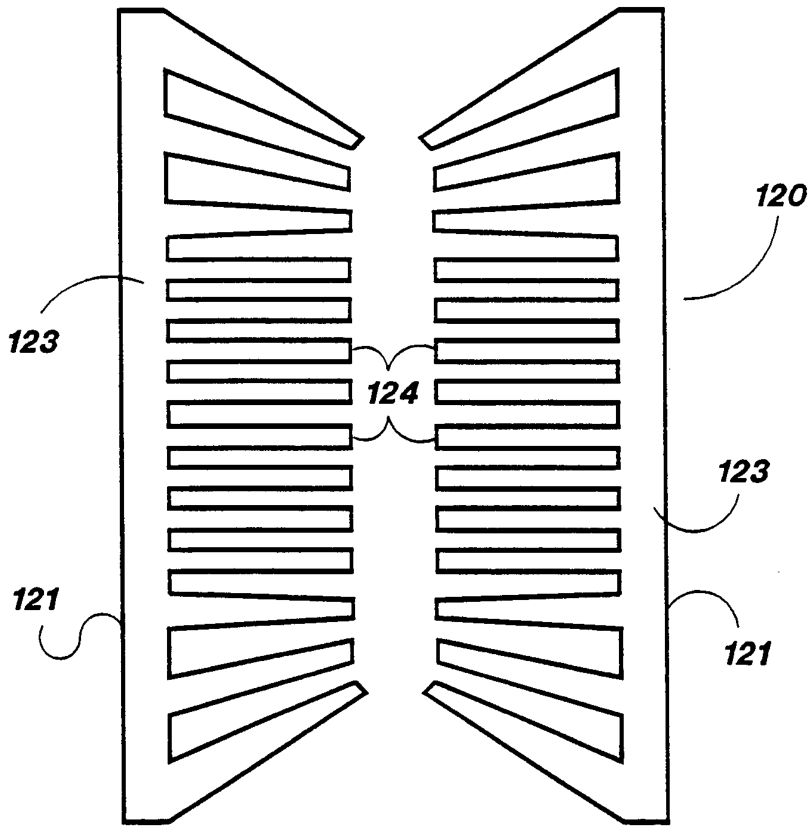

FIG. 19

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US94/12588

A. CLASSIFICATION OF SUBJECT MATTER

IPC(6) :H05H 1/00
US CL : 156/345,643; 118/723I; 204/298.08,298.31,298.34; 315/111.21,111.41
According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

U.S. : 156/345,643; 118/723I; 204/298.08,298.31,298.34; 315/111.21,111.41

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	US, A, 5,261,962 (HAMAMOTO ET AL) 16 November 1993; see the entire document.	1-26
Y	US, A, 4,948,458 (OGLE) 14 August 1990; see the entire document.	2-4,27-31

☐ Further documents are listed in the continuation of Box C. ☐ See patent family annex.

* Special categories of cited documents:

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier document published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
02 FEBRUARY 1995	14 FEB 1995

Name and mailing address of the ISA/US	Authorized officer
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