(54) VERY LARGE AREA/VOLUME MICROWAVE
ECR PLASMA AND ION SOURCE

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156/345.42; 315/111.21

See application file for complete search history.

(56) References Cited

U.S. PATENT DOCUMENTS
5,203,960 A 4/1993 Dandl ...................... 156/643
5,324,362 A 6/1994 Schneider et al. .... 118/723 MP
5,370,765 A 12/1994 Dandl ...................... 156/643
5,707,452 A 1/1998 Dandl ...................... 118/723 MW

FOREIGN PATENT DOCUMENTS
JP 06151092 A 5/1994

* cited by examiner

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(57) ABSTRACT

The present invention is an apparatus and method for producing
very large area and large volume plasmas. The invention
utilizes electron cyclotron resonances in conjunction with
permanent magnets to produce dense, uniform plasmas for
long life ion thruster applications or for plasma processing
applications such as etching, deposition, ion milling and ion
implantation. The large area source is at least five times larger
than the 12-inch wafers being processed to date. Its rectan-
gular shape makes it easier to accommodate to materials
processing than sources that are circular in shape. The source
itself represents the largest ECR ion source built to date. It is
electrodeless and does not utilize electromagnets to generate
the ECR magnetic circuit, nor does it make use of windows.

20 Claims, 4 Drawing Sheets
FIGURE 3
Disk shaped multi-slotted antenna designs have been used in the past to circumvent the aforesaid issues. These sources require, however, an insulating window for operation, i.e., for impedance matching and shielding. The insulating window, typically boron nitride makes such devices impractical for ion sources or ion thruster applications because the insulating window acquires over time a coating due to wear of the extraction grids. Said coating will ultimately prevent microwaves from penetrating the source and thus plasma production will cease.

The production of large-area plasmas that are also large in volume and provide dense plasmas is much sought after in the area of electric propulsion and plasma processing. Achieving these plasma characteristics is generally difficult from the standpoint of issues such as recombination, collisional losses and diffusion, all of which reduce discharge efficiency and uniformity of the discharged reaction mass. Moreover, the design of plasma generators that are intended for use in electric propulsion and plasma processing applications tend toward the production of plasma discharges having minimal internal erosion of the source. From an electric propulsion thruster standpoint, this design goal provides extended operation lifetime. For plasma processing, it reduces the amount of contamination of the materials being processed.

It is also important that plasma discharges take place at reduced pressures. Hollow cathode based sources in a multipole configuration can be implemented to generate reasonably large discharge plasmas. However, such discharges tend to be of poor uniformity and to introduce erosion products due to cathode degradation (as it is exposed to the discharge plasma and bombarded by high-energy discharge ions). In this respect, conventional hollow cathode based discharge sources are not a solution to long life and low erosion plasma sources.

The prior art evidenced in patent literature shows various microwave, permanent magnet, ECR plasma sources, but they suffer from limitations that the present invention overcomes.

U.S. Patent Application 2004/0045674 Al to Ishii, et al., “Radial Antenna and Plasma Device Using It,” describes a general microwave discharge, not an electron cyclotron resonance discharge (ECR). In this system, the microwave discharge is fundamentally limited in maximum plasma density, efficiency, and pressure. It is not an efficient ion source at the kinds of low pressures that are desirable for directional etching and sputter deposition applications in microelectronics. The invention of Ishii, et al., also uses a dielectric window, which can be problematic for both ion thruster uses and many deposition microelectronics reactors where metal vapor is present in the plasma. Metallic ions and atoms can condense on the window, forming a layer that eventually prevents any microwave power from entering the system. Additionally, the device of Ishii, et al., utilizes a coaxial line connection to the slotted antenna, which limits the amount of power, plasma density and thus the maximum processing applications to which a source can be built, thus limiting the ability to scale it up without recourse to a complete system redesign to scale up to a larger size.


US 7,493,869 B1

application of the device. In this regard, its size is limited and
can be scaled up only with difficulty.

U.S. Patent Application 2002/0121344 A1, to Noguchi,
"Plasma Generating Device and Plasma Processing Apparatus Comprising Such a Device," utilizes the same physics described in the patents described above. Power is fed to it by means of a coaxial line.

Japanese Patent 06151092 A, to Kyoiichi, "Microwave Plasma Treatment Device," also describes a microwave discharge device that is similar to the ones taught in the foregoing patents. It does not describe a high density low pressure ECR source.

Japanese Patent 06158298 A, to Mutsumi, et al., "Plasma Treatment Device," does not describe microwave plasma of any sort. It describes a RF glow discharge for plasma processing applications. Such devices operated at pressures ~1 Torr and plasma densities are low and not particularly suited for etching or Sputter deposition. Sputter contamination is an issue for such a source.


U.S. Pat. No. 5,324,362, to Schneider, et al., "Apparatus for Treating Substrates in a Microwave-Generated Gas-Supported Plasma," apparently refers to a US patent WO 91/12353. This technology suffers from limitations described above in comments 1-4. As a sputtering source it could introduce contaminants in a deposition or etching plasma. It also presents a lifetime issue as the antenna would be subject to sputtering. The source also utilizes a microwave window, which has disadvantages described herein.

U.S. Pat. No. 6,376,028, to Laurent, et al., "Device and Method for Treating the Inside Surface of a Plastic Container with a Narrow Opening in a Plasma Enhanced Process," does not describe a plasma source but rather a device and process that requires a plasma (preferably microwave generated). It is not applicable to the present invention.

U.S. Pat. No. 6,153,977, to Tainar, et al., "ECR Type Plasma Generating Apparatus," refers to an ECR source that utilizes a helical antenna that presumably launches a directed microwave beam toward and ECR zone established by two permanent magnets in opposition. It is inherently a small diameter device, and the ECR zone must be established between two closely spaced magnets. The device is not scalable to larger dimensions of the sort useful for large area plasma processing, high current, or long life ion thruster applications. Moreover, it is limited with respect to plasma density, which means that a workpiece to be processed must rely on the diffusion of the magnetized plasma, which is in general a slow process and can result in non-uniformities. And because it has an internal antenna it will be subject to sputter erosion limitations on service life, while also generating contaminants. The outer ceramic shield would be subject to the formation of metal coatings over time, which could affect the microwave coupling and thus the overall operation. Also because the device is coaxially fed, it is inherently limited to reduced microwave power.

U.S. Pat. No. 5,707,452, to Dandl, "Coaxial Microwave Apparator for an Electron Cyclotron Resonance Plasma Source," describes a permanent magnet ECR source that utilizes internal coaxially fed antennas immersed in ECR zones to produce plasma. This use of the coax fed antennas circumvents issues of a similar device patented by Dandl: U.S. Pat. No. 5,203,960 and U.S. Pat. No. 5,370,765 which utilize internal antennas that are subject to erosion and therefore become likely plasma contamination sources. Additionally, as each internal antenna is coaxially fed, which makes them power limited.

U.S. Pat. No. 5,203,960, to Dandl, "Method of Operation of Electron Cyclotron Resonance Plasma Source," and U.S. Pat. No. 5,370,765, also to Dandl, "Electron Cyclotron Resonance Plasma Source And Method of Operation," cannot be utilized efficiently at lower, more commercially assessable frequencies such as 2.45 GHZ. Patent '960 has cylindrical geometry which means that scaling to larger volumes requires a complete redesign of the magnetic circuit.

U.S. Pat. No. 6,322,662, to Ishii, et al. "Plasma Treatment System," utilizes a coax fed slotted antenna which inherently limits power and complicates implementation, as the coax feed would necessarily be water cooled at modest powers. It also uses a ceramic microwave window which would be subject to coating and so preclude its application to etching and deposition plasmas where metal vapors could be deposited on the ceramic. Additionally, the slotted antenna geometry of this invention is complicated and its overall layout does not lend well to scaling up in power. The antenna geometry is sophisticated, thereby imposing or requiring significant fabrication effort. Additionally, this invention is not an ECR source, but rather utilizes microwave energy to directly sustain the discharge via pair production. In this regard, it has to operate at high background pressures that limit its uses. In general, the devices described in the Dandl patents, by virtue of the plasma production approach, will likely not scale increasing diameter. The ECR zones are not coupled via the ring cusp magnetic circuit, which allows for very large area volume plasma production with straightforward scaling.

SUMMARY OF THE INVENTION

The present invention is a large electrodeless and windowless plasma source comprising a plasma chamber defining an enclosed and elongated prismatic volume and comprising a rectangular top wall having an inner planar surface, a rectangular bottom wall having an inner planar surface, two parallel quadrangular end walls having inner planar surfaces having centroids that define a length axis, a planar rectangular back portion having a height dimension and a planar rectangular exit plane having a height dimension and a width dimension and a perpendicularly oriented prismatic waveguide microwave antenna having a main axis and a plurality of matched slot pairs on one face feeds microwave energy into the plasma chamber, which contains a magnetic circuit comprising a first magnetic circuit portion and a second magnetic circuit portion. A means for injecting gases into the plasma chamber is provided. The prismatic plasma chamber can be a rectangular volume defined by the planar inner surfaces of the rectangular top wall and the rectangular bottom wall which are parallel to one another, the two parallel quadrangular end walls having inner planar surfaces, and the planar rectangular back portion and the planar rectangular exit plane which are parallel to one another. The main axis of the slotted waveguide microwave antenna and the length axis of the plasma chamber that is defined by centroids of the two parallel quadrangular end walls and the planar rectangular back portion. The first magnetic circuit portion is comprised of at least two linear magnets mounted external to the slotted waveguide microwave antenna and parallel to the main axis of the slotted waveguide and oriented into the plasma chamber, and the at least two linear magnets are permanent magnets having magnetic poles that are oriented in the same direction. The second magnetic circuit portion is comprised of a plurality of spaced apart linear magnets having magnetic poles and disposed about the inner top and bottom walls and the end walls of the
The present invention is a method of creating a large electrodeless and windowless plasma source, the method characterized by the steps of assembling a plasma chamber enclosed within an elongated prismatic volume whose shape is defined by a rectangular top wall having an inner planar surface, a rectangular inner bottom wall having an inner planar surface, two parallel quadrangular end walls having inner planar surfaces and centroids that define a length axis of the plasma chamber, a planar rectangular back portion, and a planar rectangular exit plane, and the further steps of affixing a slotted waveguide microwave antenna having a main axis, at least two linear permanent magnets oriented parallel to said main axis and having magnetic poles, and a plurality of matched slot pairs on one face of the antenna to the planar rectangular exit plane so as to focus the exiting plasma beam of ions. The enclosed prismatic volume can, as an alternative to the rectangular volume described above, be trapezoidal in cross-sectional shape when viewed along the length axis defined by the centroids of the two parallel quadrangular end walls, said trapezoidal cross-sectional shape being further defined by the height dimension of the planar rectangular back portion being less than the height dimension of the planar rectangular exit plane, while the two parallel quadrangular end walls are trapezoidal in shape. Ion optics can be used as well with the trapezoidal shaped plasma chamber.

The present invention is a method of creating a large electrodeless and windowless plasma source, the method characterized by the steps of assembling a plasma chamber enclosed within an elongated prismatic volume whose shape is defined by a rectangular top wall having an inner planar surface, a rectangular inner bottom wall having an inner planar surface, two parallel quadrangular end walls having inner planar surfaces and centroids that define a length axis of the plasma chamber, a planar rectangular back portion, and a planar rectangular exit plane, and the further steps of affixing a slotted waveguide microwave antenna having a main axis, at least two linear permanent magnets oriented parallel to said main axis and having magnetic poles, and a plurality of matched slot pairs oriented into the prismatic volume of the plasma chamber, disposing within the prismatic volume of the plasma chamber a plurality of mutually adjacent, non-coplanar permanent magnet loops having magnetic poles of opposite orientation that are closest to the slotted waveguide microwave antenna and providing one or more inlets for a gas to be ionized. The method is further characterized by alignment of the main axis of the slotted waveguide microwave antenna parallel to the length axis defined by the centroids of the quadrangular end walls and includes the further step of orienting the magnetic poles of each mutually adjacent non-coplanar permanent magnet loop in a direction opposite those of adjacent loops whose magnetic poles must be oriented such that each of the at least two linear permanent magnets affixed to the slotted waveguide microwave antenna are oriented in a single direction that is opposite that of the magnetic pole of the permanent magnet loop that is closest to the at least two linear permanent magnets. The method can also include the further step of installing ion optics means across the planar rectangular exit plane.

**BRIEF DESCRIPTION OF THE FIGURES**

The structure, operation, and advantages of the present invention will become apparent upon consideration of the accompanying FIGURES. The FIGURES are intended to be illustrative, not limiting. Certain elements in some of the FIGURES may be omitted, or illustrated not-to-scale, for illustrative clarity. The cross-sectional views may be in the form of "slices," or "near-sighted" cross-sectional views, omitting certain background lines which would otherwise be visible in a "true" cross-sectional view, for illustrative clarity.

Although the invention is generally described in the context of these preferred embodiments, it should be understood that the FIGURES are not intended to limit the spirit and scope of the invention to these particular embodiments.

Certain elements in selected ones of the FIGURES may be illustrated not-to-scale, for illustrative clarity. The cross-sectional views, if any, presented herein may be in the form of "slices," or "near-sighted" cross-sectional views, omitting certain background lines which would otherwise be visible in a true cross-sectional view, for illustrative clarity.

Elements of the FIGURES can be numbered such that similar (including identical) elements may be referred to with similar numbers in a single FIGURE. For example, each of a plurality of elements collectively referred to as 199 may be referred to individually as 199a, 199b, 199c, etc. Or, related but modified elements may have the same number but are distinguished by primes. For example, 109, 109', and 109" are three different elements which are similar or related in some way, but have significant modifications, e.g., a tire 109 having a static imbalance versus a different tire 109' of the same design, but having a couple imbalance. Such relationships, if any, between similar elements in the same or different figures will become apparent throughout the specification, including, if applicable, in the claims and abstract.

The structure, operation, and advantages of the present preferred embodiment of the invention will become further apparent upon consideration of the following description taken in conjunction with the accompanying FIGURES, wherein:

- FIG. 1A is an orthogonal schematic cut-away end view of one embodiment of the invention;
- FIG. 1B is an orthogonal schematic front view of the embodiment of FIG. 1A;
- FIG. 1C is an oblique schematic view of the embodiment of FIG. 1A;
- FIG. 1D is an orthogonal schematic cut-away end view of a second embodiment of the invention;
- FIG. 1E is an orthogonal schematic front view of the embodiment of FIG. 1D;
- FIG. 2A is an orthogonal front view of a three-magnet slotted waveguide antenna and plasma source;
- FIG. 2B is an oblique view of the waveguide antenna of FIG. 2A;
- FIG. 2C is an orthogonal front view of a two-magnet slotted waveguide antenna and plasma source;
- FIG. 3 is an end-on schematic view of one embodiment of the invention, showing the magnetic circuit and the operation of the ion optics; and
- FIG. 4 is an oblique exploded view of an existing embodiment of the present invention.

**DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS**

The present invention is a large area and large volume microwave electron cyclotron resonance (ECR) plasma and ion source that can be used as either a high density, large area plasma source and/or as an ion source. It is electrodeless and windowless. Its applications include materials processing operations such as ion milling and ion implantation and ion propulsion for space vehicles. An analysis of the performance of the present invention, entitled, "High Power ECR Ion Thruster Discharge Characterization," was presented by the
proximity of the radiating slots 18, more or less normal to the
could as well be so oriented. In either case, north or south, the
height dimension H and a perimeter 13. Injection of gas to be
same so as to create magnetic field lines that are, at least in the
planar surface and a rectangular bottom wall 17b that also has
magnets 16a,16b are the elements of a first magnetic circuit portion 16' of a total
magnetic circuit 11 (FIG. 3). As described below, this first
magnetic circuit 16' might include a third magnet between the
two shown, 16a,16b, according to the frequency of the micro-
waves being used. Also as described below, plasma formation
takes place due to the interaction of gas atoms with
microwaves. The spaced apart permanent magnets 16a,16b
are matched pairs, as discussed in detail in an earlier patent
application Ser. No. 10/925,499 entitled, "Slotted Antenna
Waveguide Plasma Source", to the present inventor which is
inventor at the International Electric Propulsion Conference
on Nov. 2, 2005, and is incorporated herein in its entirety by
reference hereto.
FIG. 1A is an orthogonal, cut-away, schematic end-view of
one embodiment 10 of a large area, large volume, plasma and
ion source 10 according to the present invention. FIG. 1B is an
orthogonal schematic front view of this embodiment of the
ion source 10, and FIG. 1C is an oblique view of the ion
source 10.

The large area, large volume, plasma and ion source 10 comprises a slotted waveguide antenna 12 that is attached to the
back wall 14 of the plasma and ion source 10. The slotted
waveguide microwave antenna 12 is rectangular in cross sec-
tion and extends along the long dimension L (FIG. 1B) on the
back wall 14 of the plasma and ion source 10. The waveguide 12 is shown with two spaced apart permanent magnets 16a,
16b that are oriented along the length L of the waveguide, as
shown in the orthogonal front view FIG. 1B wherein are shown the microwave radiating slots 18 whereas plasma forma-
tion takes place due to the interaction of gas atoms with
microwaves. The spaced apart permanent magnets 16a,16b
are oriented such that their north poles (I) are oriented
opposite to that of the preceding ring 36a. Additionally, the
third magnet ring 36a, which is closest to the slotted
waveguide microwave antenna, is opposite that of the
waveguide magnets 16a,16b and 34 according to the microwave
frequency, which is 5.85 GHz, versus 2.45 GHz used with the
two-magnet set up shown in FIGS. 1A,1B and 1C. Either
frequency, 5.85 GHz or 2.45 GHz, can be used in either of the
embodiments 10 and 40 shown in FIGS. 1A through 1E, though with adjustments in the number of waveguide magn-
ets 16a,16b and 34 according to the microwave frequency
being used. In FIG. 1E, the three waveguide magnets 34 are
shown as having their south poles facing outward.

Three spaced apart planar rectangular magnetic loops or
rings 36a,36b,36c are shown disposed around the inner por-
tion of the housing 30. The magnet planar loops 36a,36b,36c
of which only the upper and lower longitudinal portions are
shown in FIG. 1E, have end segments (out of view in the
FIGURE) which complete rectangular shaped circuits about
the interior of the volume defined by the housing 30. The
magnet planar loops 36a,36b,36c, and the corresponding
magnet rings 20 in the rectangular plasma chamber embodi-
ment portrayed in FIGS. 1A,1B and 1C, are the components
of the secondary magnetic circuit portion 36' of this embodi-
ment 40. Note in FIG. 1E that the orientation of the magnetic
poles of the magnet ring 36a, which is closest to the slotted
waveguide microwave antenna, is opposite that of the
waveguide magnets 34 that comprise the primary magnetic
circuit portion 34' of this embodiment 40.

Likewise, magnet ring 36b, which also extends around the
rectangular interior of the housing 30, has its poles oriented
opposite to that of the preceding ring 36a. Additionally, the
third magnet ring 36c is disposed behind the forward flange
31 and has its north poles oriented so as to face into the
volume defined by the housing 30. The magnetic circuit loops
are made of lots of little magnets that are mounted in a linear
way around the prismatic plasma chamber volume 21. No ion
optics are shown with the embodiment 40 of FIGS. 1D and
1E.

FIGS. 2A,2B and 2C show views of two embodiments of
the slotted waveguide portion of the present ion and plasma
source invention. FIG. 2A shows a slotted waveguide 50 in
orthogonal longitudinal front view and in cross sectional end
view. Three spaced apart permanent magnets 52 are separated
by slots 54 in the body 56 of the waveguide 50. The slots 54
are matched pairs, as discussed in detail in an earlier patent
application Ser. No. 10/925,499 entitled, "Slotted Antenna
Waveguide Plasma Source", to the present inventor which is
plane of the radiating slots. The poles of the secondary mag-
nets rings 20 (20a,20b,20c,20d in FIG. 3) alternate in ways
described below.

FIG. 1C is an oblique schematic view of the ion source
invention 10, showing the slotted antenna rectangular
waveguide 12 attached to the back 14 of housing 17. The
waveguide magnets 16a,16b are shown, as are the radiating
slots 18. Also shown in FIG. 1C is the ion optics means 24
which comprises two component electrical screen or grids
24a,24b, which are shown placed forward of the main
body 17 of the source 10. When the ion source invention 10 is
used as a high-specific-impulse thruster, the grids 24a,24b of
the ion optics 24 would be attached against the front perimeter flange 13. The ion optics 24 would also be
used when the ion/plasma source 10 is used in certain, but not
all, materials processing operations such as ion milling and
ion implantation.

FIGS. 1D and 1E show two orthogonal schematic views of
a second embodiment 40 of the present plasma source invention
wherein the housing 30 opens outward from the slotted
waveguide 32 and encloses a plasma chamber 30' that is a
prismatic volume. The waveguide 32 is shown in FIGS. 1D
and 1E with three spaced-apart waveguide magnets 34. This
different number of magnets is related to the microwave fre-
quency, which is 5.85 GHz, versus 2.45 GHz used with the
two-magnet set up shown in FIGS. 1A,1B and 1C. Either
frequency, 5.85 GHz or 2.45 GHz, can be used in either of the
embodiments 10 and 40 shown in FIGS. 1A through 1E, though with adjustments in the number of waveguide magn-
ets 16a,16b and 34 according to the microwave frequency
being used. In FIG. 1E, the three waveguide magnets 34 are
shown as having their south poles facing outward.

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back wall 14 of the plasma and ion source 10. The slotted
waveguide microwave antenna 12 is rectangular in cross sec-
tion and extends along the long dimension L (FIG. 1B) on the
back wall 14 of the plasma and ion source 10. The waveguide 12 is shown with two spaced apart permanent magnets 16a,
16b that are oriented along the length L of the waveguide, as
shown in the orthogonal front view FIG. 1B wherein are shown the microwave radiating slots 18 whereas plasma forma-
tion takes place due to the interaction of gas atoms with
microwaves. The spaced apart permanent magnets 16a,16b
are oriented such that their north poles (I) are oriented
opposite to that of the preceding ring 36a. Additionally, the
third magnet ring 36a, which is closest to the slotted
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tion of the housing 30. The magnet planar loops 36a,36b,36c
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FIGURE) which complete rectangular shaped circuits about
the interior of the volume defined by the housing 30. The
magnet planar loops 36a,36b,36c, and the corresponding
magnet rings 20 in the rectangular plasma chamber embodi-
ment portrayed in FIGS. 1A,1B and 1C, are the components
of the secondary magnetic circuit portion 36' of this embodi-
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waveguide microwave antenna, is opposite that of the
waveguide magnets 34 that comprise the primary magnetic
circuit portion 34' of this embodiment 40.

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rectangular interior of the housing 30, has its poles oriented
opposite to that of the preceding ring 36a. Additionally, the
third magnet ring 36c is disposed behind the forward flange
31 and has its north poles oriented so as to face into the
volume defined by the housing 30. The magnetic circuit loops
are made of lots of little magnets that are mounted in a linear
way around the prismatic plasma chamber volume 21. No ion
optics are shown with the embodiment 40 of FIGS. 1D and
1E.

FIGS. 2A,2B and 2C show views of two embodiments of
the slotted waveguide portion of the present ion and plasma
source invention. FIG. 2A shows a slotted waveguide 50 in
orthogonal longitudinal front view and in cross sectional end
view. Three spaced apart permanent magnets 52 are separated
by slots 54 in the body 56 of the waveguide 50. The slots 54
are matched pairs, as discussed in detail in an earlier patent
application Ser. No. 10/925,499 entitled, "Slotted Antenna
Waveguide Plasma Source", to the present inventor which is
incorporated in its entirety herein. A matched pair consists of alternating slots displaced by one half of a wavelength, or equivalent multiple, from slot center to center. The slots 56 alternate about the centerline CL (denoted in FIG. 2A) of the mid-plane of the waveguide 50 and, when mounted upon the back surface 14 of the invention the matched slot pairs are oriented into the prismatic volume of the plasma chamber 21. The main difference between the slotted antenna geometry of the present invention and the one described in the "Slotted Antenna Waveguide Plasma Source" disclosure is the absence of a center line magnet when the present plasma source invention operates with higher frequency microwaves (5.85 GHz), as shown in FIG. 2C. That is to say, at the 2.45 GHz operating frequency, the center line magnet 54' (located between slots 56) was used, but at 5.85 GHz, the center magnet was eliminated to improve performance. At the higher frequency, center-row magnets interfere with microwave launching, giving rise to significant reflection. The north poles (N) of the magnets 52 are shown oriented normal to the waveguide body 56. FIG. 2B is an oblique view of the slotted waveguide 50. Microwaves 57 enter one end 58 of the waveguide 50, along the waveguide main axis 60. A complete description of the slotted waveguide antenna portion of the present invention is given in the aforementioned disclosure, "Slotted Antenna Waveguide Plasma Source." Note, with respect to FIGS. 1A,1B,1C and 2B that the waveguide main axis 60 is parallel to and spaced apart from the length axis 17c.

FIG. 2C shows a slotted waveguide 62 in orthogonal longitudinal front view and also in cross sectional end view 63, with slots 64 and two spaced apart permanent magnets 66. That use of two instead of three magnets 66 reflects the intended microwave frequency of 5.85 GHz. South poles (S) of the permanent magnets 66 are shown facing outward, whereas the north poles (N) face inward with the north poles (N) facing outward is equally possible.

In general, waveguide sizes are standardized such that the waveguide's characteristics are matched with the wavelength of the microwave radiation to be used. For each waveguide size, there is a specific frequency range over which the waveguide will operate best. Also, in relation to the slotted waveguide portion of the present invention the magnetic circuit near the waveguide slots, which is also called herein the first magnetic circuit portion, allows for gas breakdown and well-matched plasma production on the outside of waveguide in the vicinity of the slots 64. The plasma that is produced as a consequence of the optimized magnetic circuit that eliminates the need for dielectric windows to aid in impedance matching. Additionally, the magnetic field profile at each slot prevents plasma from backflowing into the slots and causing breakdowns there, and the magnetic field at and inside the slots is not sufficient to produce ECR so no plasma production can take place inside of the waveguide. Finally, the use of multiple slots reduces the electric field at each slot and thereby minimizes slot arcing that could be caused by the presence of the plasma, which thereby eliminates the need for a dielectric window. Plasma ions that are created near the radiating slots 54 (FIGS. 2A,2B), or 64 (FIG. 2C), emerge into the larger contained volume 21 (i.e., the plasma chamber of FIG. 1A) to create a plasma volume 22 that, in the illustration of FIG. 1A, progresses to the right in the FIGURE, through the system of plasma optics 24 comprising the two grids 24a and 24b. The planar secondary magnetic loops 20 in FIGS. 1A and 36a,36b,36c in FIGS. 1D,1E serve to direct the plasma in the directions indicated. The spacing of the planar magnet loops with respect to one another and in relation to the linear magnetic 16a,16b disposed upon the waveguide 12. The planar secondary magnetic loops are aligned such that the magnet sides run parallel with the long dimension of the slots so as to ensure a strong magnetic field in the region of the slots. Permanent magnets used in this work had surface field strengths between 2.8 kG and 3 kG, which is sufficiently strong to achieve ECR all the way up to microwave frequencies of 6 GHz. At higher frequencies, stronger magnets would have to used.

FIG. 3 shows in cross-sectional end view the plasma source 10 (of FIGS. 1A,1B and 1C) and its magnetic circuit 11 which arises due to the orientation of the poles (N and S) of the magnet rings 20a,20b,20c,20d. The ring pairs are disposed around the rectangular interior perimeter of the rectangular housing 17 and together comprise the secondary magnetic circuit elements 20' of the magnetic circuit 11. The orientation of the poles of the magnet rings alternates, as illustrated with Ns and Ss. The magnetic circuit 11 is created by the field lines of the magnet rings. The process of electron cyclotron resonance takes place in the vicinities of the magnet rings 20a,20b,20c,20d as electrons that have been excited by the microwaves spiral into and out of the densest portions of the magnetic field lines close to the magnet rings. The fast moving electrons induce further ionization of atoms of the feed gas when electrons collide with them, the result being the formation of a plasma within the contained volume or plasma chamber 21.

Across the exit plane 15 of the plasma chamber 21 is disposed the screen grid 24a portion of the ion optics 24. The grid 24a is mounted upon a suitable first insulating ring 23 attached between the periphery of the screen grid 24a and the exit flange 13. Axially outward of the screen grid 24a, an accelerator grid 24b is mounted, for example on a suitable second insulating ring 25 attached between the periphery of the screen grid 24a and the inner perimeter of the accelerator grid 24b. As is conventional in the art, the screen grid 24a is electrically connected to a positive terminal of a screen voltage power supply 42, for extracting electrons from plasma 22 in the plasma chamber 21. Furthermore, the accelerator grid 24b is electrically connected to a negative terminal of an accelerator voltage power supply 44, for accelerating positive ions from the plasma 22 (that have been partially ionized by electrons) outward in a positive ion stream 41. A negative terminal of the screen voltage power supply 42 is tied to a positive terminal of the accelerator voltage power supply 44 through a common junction point 43.

To prevent a positive space charge from forming as an ion cloud that could obstruct or impede the ion stream 41, a neutralizer 46 is employed to generate a stream of electrons 47 that will recombine with the ions in the ion stream 41, thereby neutralizing the cloud back to an uncharged inert gas. A terminal of the neutralizer 46 is connected to the common junction point 43, thereby establishing an effective ground reference for the system, and also in effect bleeding off the electrons extracted by the screen grid 24a. For long service life (e.g., 10 years continuous operation) with a minimum amount of erosion, the screen grid 24a and the accelerator grid 24b are composed of pyrolytic graphite. Furthermore, it should be noted that a uniform dense ECR plasma as provided above, can be generated in the plasma source invention in FIGS. 1A,1B,1C,1D,1E which is used in the creation of a vacuum insulating layer for the formation of a plasma mass spectrometer.
comprising the secondary magnetic circuit 20, and the magnets 16a,16b comprising the primary magnetic circuit 16, the orientation of the poles of the first secondary or intermediate magnet ring 20a is such that a one of its first (S) and second (N) magnetic poles is against the outer housing 17 and the one magnetic pole's opposed magnetic pole is facing into the plasma chamber 21. The annular exit flange 13, which is composed of a ferromagnetic material, and that is attached to and extends into the exit edge of the plasma chamber 21 at the exit plane 15, has attached inside it a rectangle shaped annular magnet ring 20d such that one of its first (N) and second (S) magnetic poles is against the exit flange 13 and the one magnetic pole's opposed magnetic pole is facing into the plasma chamber 21. Thereby, the magnetic circuit 11 derives from the magnet rings 20a,20b,20c and 20d and also the magnets 16a,16b, all of which are composed of permanent magnet material such that inward facing magnetic poles (N, S) alternate polarity with respect to adjacent magnet rings while proceeding along the wall rectangular portion of the housing 17. The waveguide magnets 16a,16b, comprising the primary magnetic circuit portions 16, are accordingly oriented, as shown in FIG. 3.

Referring once again to the FIGS. 1A through 1C, the slotted antenna rectangular waveguide 12 injects microwaves into a rectangular discharge chamber 21 contained within the housing 17. Because the waveguide antenna 12 extends the length L of the back 14 of the discharge chamber 21, it allows for distributed plasma production. Unlike single hollow cathode DC devices, the distributed plasma 22 that is produced gives rise to distributed ionization thereby improving discharge uniformity. Coupled to the slotted antenna 12 is the aforementioned magnetic circuit structure consisting of the waveguide magnets 16a,16b and the secondary magnets 20 which are arranged so as to generate contours on which ECR plasma production takes place. The secondary magnets 20a, 20b, 20c, 20d, in conjunction with the magnets 16a,16b, create the magnetically connected magnetic circuit 11 that 1) confines the produced discharge plasma and 2) circulates the hot electrons produced in the ECR zones.

The embodiments 10 and 30 in FIGS. 1D and 1E respectively have been demonstrated using two different microwave frequencies: 2.45 Ghz and 5.85 Ghz. While waveguides designed to handle 2.45 Ghz are commercially readily available, 5.85 MHz can be used for those applications requiring very high plasma densities even though power supplies at 5.85 Ghz are more expensive than at 2.45 Ghz.

FIG. 4 is an oblique exploded view the structural components of an actual embodiment of the plasma source 70 according to the present invention. When assembled, the plasma source 70 is contained with a main support frame 72 that holds the support structure 74 for the secondary magnets or magnet rings (not shown), along with the back plate 76 has attached to it the spaced-apart waveguide magnets 78 that straddle the radiating slots 80. The waveguide 82, as shown in the exploded view, has an open face 83. When the waveguide 82 is mounted against the back plate 76, the waveguide becomes complete with its waveguide magnets 78 and radiating slots 80 whereat the plasma forms and emerges into the volume V of the support structure 74 that holds the secondary magnets. Bracket 86 enables the waveguide 82 to be connected to a microwave source (not shown). When the plasma source 70 is assembled, it has a back cover 88 and top and bottom covers 90a,90b and side covers 92a,92b. The ion optics grids 94a,94b are held in place against the frame 72 and the housing 74 by the forward frame 96.

General Comments

1. Completely electrodeless (erosion issues eliminated);
2. Plasma source does not require a microwave window;
3. Very large area, large volume plasmas are possible by simply extended the length of the slotted antenna and housing of secondary magnetic circuit; 4. Scalable to very high powers (minimal modifications to magnetic circuit required to make device larger) (also waveguide approach allows for operation up to 10 to 100 kW of input power); more specifically, the characteristic length dimension, parallel to the main axis of the slotted antenna waveguide, can be increased without limit;
5. Utilizes permanent magnets for ECR and plasma confinement;
6. Adaptable to operate over a range of frequencies (2.45, 5.85 GHz already demonstrated); in fact, compared to large circular plasma sources, the present rectangular unit has a broader frequency range.
7. Plasma in interior of device is not magnetized making it desirable for ion beam applications (ions are magnetized); the invention has been operated as a high energy ion source; beam power 13 kw;
8. Different types of gases can be used (reactive or non-reactive);
9. Metal vessels plasma can also be processed in the discharge chamber since there is no microwave window at the source;
10. Source can operated at very low background pressures 10^-6 to 10^-13 Torr;
11. The rectangular shape lends itself to industrial applications;
12. Prototype source represents the largest, most powerful ECR source ever built;
13. The device operates at multiple frequencies, requiring only change in size waveguide of slotted antenna;
14. Device operates with permanent magnets. Large volume minimizes heat load to magnets so that device can operate over a wide power range without overheating magnets;
15. Device though large volume is self starting;
16. Device though large volume is also capable of operating over a wide range of flow rates;
17. Device operates on different gases including but not limited to air, xenon, and CO2;
18. Emission spectra of device discharge plasma revealed only singly charge ions and no neutrals. The lack of multiple charged species in plasma suggests that erosion due to multiply charge species is minimal;
19. The large volume source is tunable over a wide power range with very low reflected powers (<10%). The discharge though high power and large volume is stable and does not mode hop;
20. The plasma is uniform in both the lateral and transverse dimensions;
21. Plasma potentials in the discharge are low, approximately 15 Volts or less, thus minimizing erosion issues; and
21. The source is scalable to larger sizes by simply extending the slotted antenna.

The large area plasma source described in this disclosure is electrodeless. It utilizes microwave electron cyclotron resonance (ECR) to generate the discharge. A slotted antenna has been implemented with a novel magnetic circuit geometry to produce a large area plasma. The source is also designed to be windowless. Both the implementation of the slotted antenna and the primary magnetic circuit allow for both large-area and large-volume plasmas to be produced. Such plasmas have been generated using this approach. For example, a source with an effective beam area of measuring 40×50 cm (and 40 cm deep) has already been tested and validated. It is scalable in power, size and plasma density. The present invention has demonstrated high plasma density operation at both 2.45 GHz and 5.85 GHz. Additionally, it has been demonstrated with the use of a permanent magnetic circuit instead of with the kinds of bulky and energy intensive electromagnets that are typically used in conventional ECR sources. The plasma source according to the present invention represents a means to generating large-area plasmas. Uniformity of the plasma can be tailored by adjusting slot and magnet locations.

The plasma source according to the present invention can be scaled upwards in its length dimension, i.e., in the direction parallel to the axis of the slotted waveguide and oriented into the plasma chamber. It can be used to process multiple work pieces such as silicon wafers, with its rectangular shape being better-suited to industrial work areas than would be circular plasma sources of comparable characteristic linear dimension. The large size and high plasma density offered by the device gives it the capacity to process many items at once, which can dramatically improve productivity of companies that produce microchips from silicon wafers, i.e., many wafers can be processed at once. The same holds true for fabs that do depositions, implantations, or etchings. This plasma and ion source can be used with reactive gases used in etching industry. Large area ion implantation source for surface modifications can also benefit from this technology.

This ion source invention offers benefits over hollow cathode technology, with perhaps the most important to the commercial industry being that a very clean (few contaminants), high volume plasma can be generated.

In the realm of ion propulsion, this invention can also be adapted to producing dense, uniform plasmas for long life ion thruster applications.

Although the invention has been shown and described with respect to a certain preferred embodiment or embodiments, certain equivalent alterations and modifications will occur to others skilled in the art upon the reading and understanding of this specification and the annexed drawings. In particular regard to the various functions performed by the above described components (assemblies, devices, circuits, etc.) the terms (including a reference to a "means") used to describe such components are intended to correspond, unless otherwise indicated, to any component which performs the specified function of the described component (i.e., that is functionally equivalent), even though not structurally equivalent to the disclosed structure which performs the function in the herein illustrated exemplary embodiments of the invention. In addition, while a particular feature of the invention may have been disclosed with respect to only one of several embodiments, such feature may be combined with one or more features of the other embodiments as may be desired and advantageous for any given or particular application.
10. The large electrodeless and windowless plasma source of claim 1 wherein:

the slotted waveguide microwave antenna is mounted to the back portion of the plasma chamber and the plurality of matched slot pairs on one face are oriented into the prismatic volume of the plasma chamber.

11. The large electrodeless and windowless plasma source of claim 1 wherein the gas injection means is disposed about the perimeter of the exit plane.

12. The large electrodeless and windowless plasma source of claim 1 wherein the exit plane of the plasma chamber has ion optics means disposed across it.

13. The large electrodeless and windowless plasma source of claim 1 wherein the enclosed prismatic volume has a trapezoidal cross-sectional shape when viewed along the length axis defined by the centroids of the two parallel quadrangular end walls, said trapezoidal cross-sectional shape being further defined by the height dimension of the planar rectangular back portion being less than the height dimension of the planar rectangular exit plane.

14. The large electrodeless and windowless plasma source of claim 1 wherein the two parallel quadrangular end walls are trapezoidal in shape.

15. The large electrodeless and windowless plasma source of claim 1 wherein the planar rectangular exit plane of the plasma chamber has ion optics means disposed across it.

16. The method of creating a large electrodeless and windowless plasma source, the method being characterized by the steps of:

assembling a plasma chamber enclosed within an elongated prismatic volume whose shape is defined by a rectangular top wall having an inner planar surface, a rectangular inner bottom wall having an inner planar surface, two parallel quadrangular end walls having inner planar surfaces and centroids that define a length axis of the plasma chamber, a planar rectangular back portion, and a planar rectangular exit plane;
affixing to the planar rectangular back portion a slotted waveguide microwave antenna having a main axis, at least two linear permanent magnets oriented parallel to said main axis and having magnetic poles, and a plurality of matched slot pairs oriented into the prismatic volume of the plasma chamber;
disposing within the prismatic volume of the plasma chamber a plurality of mutually adjacent, non-coplanar permanent magnet loops having magnetic poles, one loop of which is closest to the slotted waveguide microwave antenna; and
providing one or more inlets for a gas to be ionized.

17. The method of claim 16 wherein the method of affixing of a slotted waveguide microwave antenna to the rectangular back portion defining the prismatic volume of the plasma chamber includes the further step of aligning the main axis of the slotted waveguide microwave antenna parallel to the length axis defined by the centroids of the quadrangular end walls.

18. The method of claim 16 wherein the method of disposing within the prismatic volume of the plasma chamber a plurality of mutually adjacent non-coplanar permanent magnet loops, one of which is closest to the at least two linear permanent magnets of the slotted waveguide microwave antenna includes the further step of orienting the magnetic poles of each mutually adjacent non-coplanar permanent magnet loop in a direction opposite those of adjacent loops.

19. The method of claim 18 wherein the method of orienting the magnetic poles of each mutually adjacent permanent magnet loop in a direction opposite those of adjacent loops includes the further step of orienting the magnetic poles of each of the at least two linear permanent magnets affixed to the slotted waveguide microwave antenna in a single direction that is opposite that of the magnetic pole of the permanent magnet loop that is closest to the at least two linear permanent magnets.

20. The method of claim 16 wherein the method of creating a large electrodeless and windowless plasma source includes the further step of installing ion optics means across the planar rectangular exit plane.