(12) INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(51) International Patent Classification:
H01J 27/00 (2006.01)

(21) International Application Number:
PCT/US2005/038600

(22) International Filing Date: 25 October 2005 (25.10.2005)

(25) Filing Language: English

(26) Publication Language: English

(30) Priority Data:
60/621,913   25 October 2004 (25.10.2004)   US

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(81) Designated States *(unless otherwise indicated, for every kind of national protection available)*: AE, AG, AL, AM, AT, AU, AZ, BA, BB, BG, BR, BW, BY, BZ, CA, CH, CN, CO, CR, CU, CZ, DK, DM, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, HR, HU, ID, IL, IN, IS, JP, KE, KG, KM, KP, KR, KZ, LC, LK, LR, LS, LT, LU, LV, LY, MA, MD, MG, MK, MN, MW, MX, MZ, NA, NG, NI, NO, NZ, OM, PG, PH, PL, PT, RO, RU, SC, SD, SE, SG, SK, SL, SM, SY, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VC, VN, YU, ZA, ZM, ZW.

(84) Designated States *(unless otherwise indicated, for every kind of regional protection available)*: ARIPO (BW, GH, GM, KE, LS, MW, MZ, NA, SD, SL, SZ, TZ, UG, ZM, ZW), Eurasian (AM, AZ, BY, KG, KZ, MD, RU, TJ, TM), European (AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, HU, IE, IS, IT, LT, LU, LV, MC, NL, PL, PT, RO, SE, SI, SK, TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, ML, MR, NE, SN, TD, TG).

Published:
— without international search report and to be republished upon receipt of that report

For two-letter codes and other abbreviations, refer to the "Guidance Notes on Codes and Abbreviations" appearing at the beginning of each regular issue of the PCT Gazette.

(54) Title: IONIZER AND METHOD FOR GAS-CLUSTER ION-BEAM FORMATION
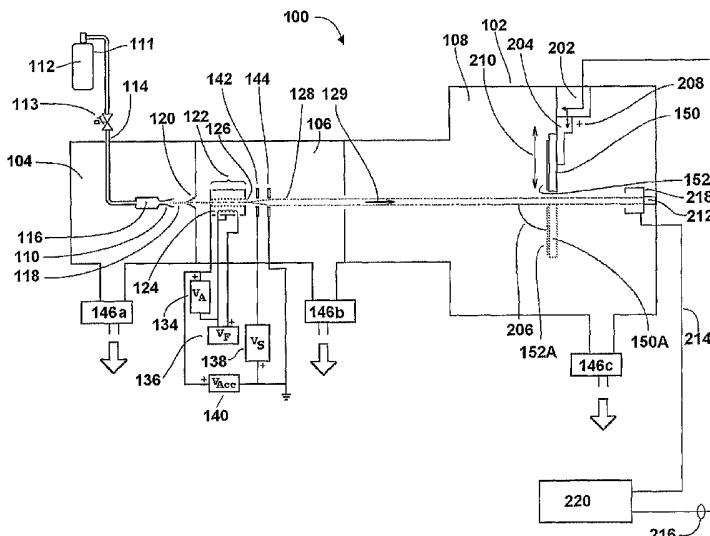
(57) Abstract: An ionizer for forming a gas-cluster ion beam is disclosed including inlet and outlet ends partially defining an ionization region traversed by a gas-cluster jet and one or more plasma electron source(s) for providing electrons to the ionizing region for ionizing at least a portion of the gas-clusters to form a gas-cluster ion beam. One or more sets of substantially linear rod electrodes may be disposed substantially parallel to and in one or more corresponding partial, substantially cylindrical pattern(s) about the gas-cluster jet axis, wherein some sets are arranged in substantially concentric patterns with differing radii. In certain embodiments, the ionizer includes one or more substantially linear thermionic filaments disposed substantially parallel to the gas-cluster jet axis, heating means, electrical biasing means to judiciously bias sets of the linear rod electrodes with respect to the thermionic filaments to achieve electron repulsion.

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IONIZER AND METHOD FOR GAS-CLUSTER ION-BEAM FORMATION

Field of the Invention

The present invention relates generally to methods and apparatus for ionizing a gas-cluster jet

5   to form a gas-cluster ion beam (GCIB) for processing the surface of a workpiece and, more

particularly, to forming a high current GCIB for workpiece processing with reduced

workpiece metals contamination.

Background of the Invention

The use of a gas-cluster ion beam (GCIB) for etching, cleaning, and smoothing surfaces is

10   known in the art (see, for example, US Patent 5,814,194, Deguchi *et al.,* incorporated herein

by reference). GCIBs have also been employed for assisting the deposition of films from

vaporized carbonaceous materials (see, for example, US Patent 6,416,820, Yamada *et al.,*

incorporated herein by reference). For purposes of this discussion, gas-clusters are nano-

sized aggregates of materials that are gaseous under conditions of standard temperature and

15   pressure. Such clusters may consist of aggregates of from a few to several thousand

molecules or more that are loosely bound to form a cluster. The clusters can be ionized by

electron bombardment, permitting them to be formed into directed beams of controllable

energy. Such ions each typically carry positive charges of $q \cdot e$ (where e is the magnitude of

the electronic charge and q is an integer of from one to several representing the charge state

20   of the cluster ion). The larger sized cluster-ions are often the most useful because of their

ability to carry substantial energy per cluster-ion, while yet having only modest energy per

molecule. The clusters disintegrate on impact, with each individual molecule carrying only a

small fraction of the total cluster energy. Consequently, the impact effects of large clusters

are substantial, but are limited to a very shallow surface region. This makes gas-cluster ions

25   effective for a variety of surface modification processes, without the tendency to produce

deeper subsurface damage, which is characteristic of conventional ion beam processing.

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Means for creation of and acceleration of such GCIBs are described in the reference (US 5,814,194) previously cited. Presently available cluster-ion sources produce cluster-ions having a wide distribution of sizes, N, up to N of several thousand (where N = the number of molecules in each cluster). In the case of monatomic gases like argon, an atom of the

5   monatomic gas will be referred to as either an atom or a molecule and an ionized atom of such a monatomic gas will be referred to as either an ionized atom, a molecular ion, or a monomer ion.

Many useful surface-processing effects can be achieved by bombarding surfaces with GCIBs.

10   These processing effects include, but are not limited to, smoothing, etching, film growth, and infusion of materials into surfaces. In many cases, it is found that in order to achieve industrially practical throughputs in such processes, GCIB currents on the order of hundreds or perhaps thousands of microamps are required. Ionizers for ionizing gas-cluster jets to form GCIBs have historically been of the electron impact type, utilizing thermoelectrons to

15   ionize gas-clusters by impact with the clusters. Such impact often ejects one or more electrons from a gas-cluster, leaving it positively charged. In U.S. Patent 6,629,508 (incorporated herein by reference), Dykstra has described several forms of prior art ionizers for GCIB formation.

20   Several emerging applications for GCIB processing of workpieces on an industrial scale are in the semiconductor field. Due to yield considerations, such applications typically require that processing steps contribute only very low levels of contamination. Although GCIB processing of workpieces is done using a wide variety of gas-cluster source gases, many of which are inert gases, in many semiconductor processing applications it is desirable to use

25   reactive source gases in the formation of GCIBs, sometimes in combination or mixture with inert or noble gases. Often halogen-containing gases, oxygen, and other reactive gases or mixtures thereof are incorporated into GCIBs, sometimes in combination or mixture with inert or noble gases. These reactive gases pose a problem for gas-cluster ionizer design for semiconductor processing because of their corrosive nature. For example, NF_3 and O_2 are

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often combined for forming GCIBs for use in etching or smoothing processes. When gas-clusters comprising NF_3 and O_2 are bombarded by electrons during ionization to form gas-cluster ions, there is a certain amount of evaporation of the gas-clusters that results, evolving corrosive gas components inside the ionizer. Since thermionic filaments used to generate

5   thermoelectrons for ionization operate at high temperatures, they are susceptible to attack by the reactive and corrosive gases that are evolved. Particularly when the partial pressures of the reactive gases reach high levels, such attack can be exacerbated and can extend to other lower temperature materials-of-construction of the ionizer as well as to the high temperature filaments. This type of reactive interaction of corrosive gas constituents with the ionizer

10   filament(s) and other materials in the ionizer has two important drawbacks. It shortens the operational lifetime of the filaments in the ionizers, and it results in the generation of small particles and molecules or ions of potential contaminants that can interfere with the yield of semiconductor processes. Specifically, since the thermionic filaments are normally metallic (often tungsten) and since other materials-of-construction of the conventional ionizers are

15   also often metal (aluminum, iron, molybdenum, etc.), the use of reactive gas components in the gas-clusters results in generation of ions, molecules, and small particles of metals and compounds containing metal atoms. In a GCIB processing tool for application in the field of semiconductor processing, or in any field of application requiring low levels of contamination, such generation of contaminants is detrimental to the GCIB processing

20   because such contaminants inevitably transport from the ionizer to the surfaces of the workpieces being processed.

In order to produce high ionization efficiency in a GCIB ionizer, it has been desirable to have available a high electron flux for impact ionization of gas-clusters. In order to produce high

25   emission currents in thermionic emission electron sources, high electric fields are commonly employed to overcome space-charge effects that otherwise tend to limit thermionic emission. An undesirable side effect of this expedient is that the energies of the impact ionization ionizing electrons are higher than desirable, often several hundred electron volts. High energy electrons may contribute to the production of higher ionization states of multiply

30   ionized gas-cluster ions. In some GCIB processing applications, large quantities of highly

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ionized (ionization state above 3 or 4) gas-cluster ions are considered detrimental to the process.

Summary of the Invention

5   It is therefore an object of this invention to provide an ionizer and methods for generating a GCIB with high ionization efficiency for high throughput processing of workpieces.

It is a further object of this invention to provide a GCIB ionizer having an extended filament lifetime when operating with gas-clusters containing reactive gas molecules.

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It is another object of this invention to provide a GCIB ionizer that generates lowered levels of contaminants even when operated in the presence of gas-clusters containing reactive gas molecules, especially for metallic contaminants.

15   An ionizer for ionizing a gas-cluster jet to form a gas-cluster ion-beam has a very transparent structure to facilitate high gas conductivity and to minimize internal pressure during ionization. A plasma source provides copious electrons at relatively low energies. The plasma source has a thermionic filament that is isolated from the gas-cluster ionization region to reduce interaction between the thermionic filament and corrosive gas components that may

20   be evolved from the gas-clusters being ionized. To a substantial degree, the design permits substitution of non-metallic construction materials to produce lowered contribution to particulate and metal contamination of the workpieces processed in a GCIB processing apparatus. Most components exposed to the gas-cluster jet and its evolution products are constructed from high purity graphite, and though a hot metallic filament is used, it interacts

25   little with any reactive gas-cluster jet evolution products. This results in extended filament operating life, and reduced contribution of contaminants from the metal filament.

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Brief Description of the Figures

For a better understanding of the present invention, together with other and further objects thereof, reference is made to the accompanying drawing and detailed description, wherein:

Figure 1 is a schematic showing the basic elements of a prior art GCIB processing apparatus;

5   **Figure 2** is a schematic illustrating a portion of a prior art gas-cluster ionizer for ionizing a gas-cluster jet;

Figure 3 is an illustration of a section of an improved gas-cluster ionizer for ionizing a gas-cluster jet according to the present invention;

Figure 4 is an illustration of exemplary electron paths within an improved gas-cluster ionizer

10   such as shown in **Fig. 3**;

Figure 5 is an illustration of a side of a further improved ionizer **400** according to an embodiment of the present invention;

Figure 6 is a cut-away illustration of an improved ionizer **400** such as shown in **Fig. 5**;

Figure 7 is a sectional view of the improved ionizer **400** shown in **Fig. 5**;

15   **Figure 8** is a detailed drawing showing configuration of a preferred embodiment of extraction apertures in a noble gas plasma electron source in accordance with the present invention;

Figure 9 is a schematic showing details of biasing of the electrodes of improved ionizer **400**;

Figure 10 is a schematic showing plasma formation and electron extraction from the noble

20   gas plasma electron source;

Figure 11 is a schematic of a second preferred embodiment of the configuration of the extraction apertures;

Figure 12 is a schematic of a third preferred embodiment of the configuration of the plasma chamber **678** and the extraction apertures **676**;

25   **Figure 13** is a schematic showing elements of a typical configuration for a GCIB processing apparatus **700** incorporating an improved ionizer **400** in accordance with the invention; and

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Figure 14 is a graph showing improvement in reduction of metals contamination in semiconductor processing due to the improved ionizer of the invention.

Detailed Description of Certain Embodiments of the Invention

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Figure 1 shows a configuration for a GCIB processing apparatus 100 of a form known in prior art, and which may be described as follows: a vacuum vessel 102 is divided into three communicating chambers, a source chamber 104, an ionization/acceleration chamber 106, and a processing chamber 108. The three chambers are evacuated to suitable operating

10   pressures by vacuum pumping systems 146a, 146b, and 146c, respectively. A condensable source gas 112 (for example argon or O_2) stored in a gas storage cylinder 111 is admitted under pressure through gas metering valve 113 and gas feed tube 114 into stagnation chamber 116 and is ejected into the substantially lower pressure vacuum through a properly shaped nozzle 110. A supersonic gas jet 118 results. Cooling, which results from the

15   expansion in the jet, causes a portion of the gas jet 118 to condense into clusters, each consisting of from several to several thousand weakly bound atoms or molecules. A gas skimmer aperture 120 partially separates the gas molecules that have not condensed into a cluster jet from the cluster jet so as to minimize pressure in the downstream regions where such higher pressures would be detrimental (e.g., ionizer 122, suppressor electrode 142, and

20   processing chamber 108). Suitable condensable source gases 112 include, but are not limited to argon, nitrogen, carbon dioxide, oxygen, NF_3, and other gases and/or gas mixtures.

After the supersonic gas jet 118 containing gas-clusters has been formed, the clusters are ionized in an ionizer 122. The ionizer 122 is typically an electron impact ionizer that

25   produces thermoelectrons from one or more incandescent filaments 124 and accelerates and directs the electrons, causing them to collide with the gas-clusters in the gas jet 118 where the jet passes through the ionizer 122. The electron impacts with clusters eject electrons from the clusters, causing a portion the clusters to become positively ionized. Some clusters may have more than one electron ejected and may become multiply ionized. Suppressor electrode 142,

30   and grounded electrode 144 extract the cluster ions from the ionizer exit aperture 126,

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accelerate them to a desired energy (typically with acceleration potentials of from several hundred V to several tens of kV), and focuses them to form a GCIB **128**. The axis **129** of the supersonic gas jet **118** containing gas-clusters is substantially the same as the axis of the GCIB **128**. Filament power supply **136** provides filament voltage V_f to heat the ionizer

5   filament **124**. Anode power supply **134** provides anode voltage V_A to accelerate thermoelectrons emitted from filament **124** to cause the thermoelectrons to irradiate the cluster-containing gas jet **118** to produce cluster ions. Suppression power supply **138** provides suppression voltage V_S to bias suppressor electrode **142**. Accelerator power supply **140** provides acceleration voltage V_{Acc} to bias the ionizer **122** with respect to suppressor

10   electrode **142** and grounded electrode **144** so as to result in a total GCIB acceleration potential equal to V_{Acc}. Suppressor electrode **142** serves to extract ions from the ionizer exit aperture **126** of ionizer **122**, to prevent undesired electrons from entering the ionizer **122** from downstream, and to form a focused GCIB **128**.

15   A workpiece **152**, which may be a semiconductor wafer or other workpiece to be processed by GCIB processing, is held on a workpiece holder **150**, which can be disposed in the path of the GCIB **128**. Since most applications contemplate the processing of large workpieces with spatially uniform results, a scanning system is desirable to uniformly scan a large-area workpiece **152** through the stationary GCIB **128** to produce spatially homogeneous

20   workpiece processing results.

An X-scan actuator **202** provides linear motion of the workpiece holder **150** in the direction of X-scan motion **208** (into and out of the plane of the paper). A Y-scan actuator **204** provides linear motion of the workpiece holder **150** in the direction of Y-scan motion **210**,

25   which is typically orthogonal to the X-scan motion **208**. The combination of X-scanning and Y-scanning motions moves the workpiece **152**, held by the workpiece holder **150** in a raster-like scanning motion through GCIB **128** to cause a uniform (or otherwise programmed) irradiation of a surface of the workpiece **152** by the GCIB **128** for processing of the workpiece **152**. The workpiece holder **150** disposes the workpiece **152** at an angle with

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respect to the axis of the GCIB **128** so that the GCIB **128** has an angle of beam incidence **206** with respect to a workpiece **152** surface. The angle of beam incidence **206** may be 90 degrees or some other angle, but is typically 90 degrees or near 90 degrees. During Y-scanning, the workpiece **152** and the workpiece holder **150** move from the position shown to

5   the alternate position "A" indicated by the designators **152A** and **150A** respectively. Notice that in moving between the two positions, the workpiece **152** is scanned through the GCIB **128** and in both extreme positions, is moved completely out of the path of the GCIB **128** (over-scanned). Though not shown explicitly in **Figure 1**, similar scanning and over-scan is performed in the (typically) orthogonal X-scan motion **208** direction (in and out of the plane

10   of the paper).

A beam current sensor **218** is disposed beyond the workpiece holder **150** in the path of the GCIB **128** so as to intercept a sample of the GCIB **128** when the workpiece holder **150** is scanned out of the path of the GCIB **128**. The beam current sensor **218** is typically a faraday

15   cup or the like, closed except for a beam-entry opening, and is typically affixed to the wall of the vacuum vessel **102** with an electrically insulating mount **212**.

A controller **220**, which may be a microcomputer based controller, connects to the X-scan actuator **202** and the Y-scan actuator **204** through electrical cable **216** and controls the X-scan

20   actuator **202** and the Y-scan actuator **204** so as to place the workpiece **152** into or out of the GCIB **128** and to scan the workpiece **152** uniformly relative to the GCIB **128** to achieve desired processing of the workpiece **152** by the GCIB **128**. Controller **220** receives the sampled beam current collected by the beam current sensor **218** by way of lead **214** and thereby monitors the GCIB and controls the GCIB dose received by the workpiece **152** by

25   removing the workpiece **152** from the GCIB **128** when a predetermined desired dose has been delivered.

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Figure 2 shows a section **300** of a prior art gas-cluster ionizer for ionizing a gas-cluster jet. The section is transverse to the cluster-ion jet axis **129**. Clusters leaving the skimmer (**120**, **Fig. 1**) and entering an ionizer will travel with roughly the sound velocity characteristic of the gas. For typical gas-cluster sizes (2000 to 15000 atoms), this corresponds to a kinetic

5   energy of 130 to 1000 eV. At these low energies, any departure from space charge neutrality within the ionizer will result in a rapid blow up of the jet with a significant loss of beam current. **Fig. 2** illustrates a prior art self-neutralizing ionizer. As with other prior art ionizers, gas-clusters are ionized by electron impact. In this design, thermoelectrons (seven examples indicated by **310**) are emitted from multiple linear thermionic filaments **302a**, **302b**, and **302c**

10   (typically tungsten) and are extracted and focused by the action of suitable electric fields provided by electron-repeller electrodes **306a**, **306b**, and **306c** and beam-forming electrodes **304a**, **304b**, and **304c**. Thermolectrons **310** pass through the gas cluster jet and the gas-cluster jet axis **129** and then strike the opposite beam-forming electrode **304b** to produce low energy secondary electrons (**312**, **314**, and **316** indicated for examples). Though (for

15   simplicity) not shown, linear thermionic filaments **302b** and **302c** also produce thermoelectrons that subsequently produce low energy secondary electrons. All the secondary electrons help ensure that the ionized-cluster jet remains space charge neutral by providing low energy electrons that can be attracted into the positively ionized gas-cluster jet as required to maintain space-charge neutrality. Beam-forming electrodes **304a**, **304b**, and

20   **304c** are biased positively with respect to linear thermionic filaments **302a**, **302b**, and **302c** and electron-repeller electrodes **306a**, **306b**, and **306c** are negatively biased with respect to linear thermionic filaments **302a**, **302b**, and **302c** Insulators **308a**, **308b**, **308c**, **308d**, **308e**, and **308f** electrically insulate and support electrodes. This self-neutralizing ionizer is very effective and achieves over 1000 μA argon GCIBs. A major limitation of the self-

25   neutralizing ionizer of **Figure 2** is that gases evolved from gas-clusters during the ionization processes produce an elevated internal pressure. With corrosive gases, particularly NF_3 in O_2, this results in attack of the various ionizer parts, particularly the linear thermionic filaments **302a**, **302b**, and **302c**. Accordingly, filament life is shortened and unacceptable metals contamination is produced on workpieces being processed by GCIB.

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Figure 3 shows a schematic section **350** of an improved gas-cluster ionizer for ionizing a gas-cluster jet. The section is transverse to the cluster-ion jet axis **129**. In this design, the large electrodes of the self-neutralizing ionizer shown in **Fig. 2** have been replaced with thin rod electrodes arranged in substantially cylindrical patterns concentric with cluster-ion jet

5   axis **129**. There are multiple linear thermionic filaments **352a**, **352b**, and **352c** (typically tungsten) disposed symmetrically about, equidistant from, and parallel to cluster-ion jet axis **129**. Multiple thin rod anode electrodes (three examples indicated by **354**) are arranged on a circle **356** that is substantially concentric with cluster-ion jet axis **129**. The anode electrodes (three examples indicated by **354**) are all biased at the same electrical potential, which is

10 positive with respect to the potentials on the linear thermionic filaments **352a**, **352b**, and **352c**. Multiple thin rod electron-repeller electrodes (three examples indicated by **358**) are arranged on a circle **360** that is substantially concentric with cluster-ion jet axis **129** and has a larger radius than the radius of the circle **356**. The electron-repeller electrodes (three examples indicated by **358**) are all biased at the same electrical potential, which is negative

15 with respect to the potentials on the linear thermionic filaments **352a**, **352b**, and **352c**. The multiple linear thermionic filaments **352a**, **352b**, and **352c** disposed symmetrically about, and equidistant from the cluster-ion jet axis **129** at a distance intermediate to the radius of circle **356** and the radius of circle **360**. All electrodes are supported at their ends by support plates not shown and the entire structure of the ionizer uses support rods (two examples indicated

20 by **362a** and **362b**) for mechanical support.

Figure 4 illustrates a numerical simulation of the improved gas-cluster ionizer shown in **Fig. 3**. In the simulation, the anode electrodes **354** (for example) are biased at V_{Acc} (the ionizer potential). The multiple linear thermionic filaments **352c**, in this example, are biased at V_{Acc}

25 $- 165V$. The electron-repeller electrodes **358**, in this example, are biased at $V_{Acc} + 325$ V. In the simulation, electric field equipotential lines **382** (examples indicated) are shown and thermoelectrons **384** (examples indicated) are shown to be extracted from linear thermionic filament **352c** (for example) and then to orbit within the ionizer until they eventually strike one of the anode electrodes **354** (for example). An example of one electron striking an anode

30 electrode is shown at **386**. Since the thermoelectrons orbit, they have a high efficiency for

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ionizing gas-clusters in the gas-cluster jet. Also, since they must eventually strike an anode electrode **354** (for example), they cause secondary emission (not shown for simplicity) of low energy secondary electrons in large quantities. As in the self-neutralizing ionizer previously described, all the secondary electrons help ensure that the ionized-cluster jet remains space-

5   charge neutral by providing low energy electrons that can be attracted into the positively ionized gas-cluster jet as required to maintain neutrality. The thin rod electrode structure of the ionizer assures high conductance for gases out of the ionizer compared to the self-neutralizing ionizer previously described (**Fig. 2**), assuring that lower operating pressures are attained within the ionizer. Because of the lower pressure, the generation of contaminant

10   ions, molecules, and particles is substantially reduced over the performance of the prior art ionizer of **Fig. 2**. However, because the hot thermionic filaments **352a**, **352b**, and **352c** are directly exposed to reactive components evolved from gas-clusters, contamination can still be high, particularly with the more corrosive gases like NF_3 - O_2 mixtures.

15   **Figure 5** is a perspective view of an improved ionizer **400** according to the invention. In order to isolate the hot thermionic metallic filaments from corrosive gas products evolved from gas-clusters, a noble gas plasma electron source replaces the thermionic filaments of prior designs as the immediate source of electrons. This ionizer has an open, thin rod electrodes, structure similar to that shown and discussed for **Figures 3 and 4** previously, for

20   low-pressure operation. Because the impact ionizing electron source is a noble gas plasma rather than a hot metal filament and because all materials of construction that are significantly exposed to corrosive or reactive gases evolved from the gas-cluster jet are high purity graphite, the generation of metallic contaminants by the ionizer is extremely low. A metal (typically tungsten) pigtail filament is employed in a plasma source to generate the

25   plasma electron source, but due to its isolation, it does not significantly interact with corrosive and reactive components of the gas-cluster jet evolution products. The improved ionizer **400** surrounds a gas-cluster jet axis **129**. The ionizer's upstream or inlet end comprises an extension tube **402**. The ionizer's downstream or outlet end comprises an exit electrode **404**. Multiple apertures **406** (three indicated for examples) admit electrons to the

30   ionizing region of the ionizer from the noble gas plasma electron source for impact ionization

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of gas-clusters traveling along a jet along gas-cluster jet axis **129**. Cutting planes, designated **A—A** and **B—B**, are indicated for orientation in subsequent figures. An electrically insulating support **408** provides mounting means for disposing the ionizer with respect to the gas-cluster jet axis **129**, while permitting electrical bias of the entire ionizer body to a high

5   voltage V_{Acc} consistent with the general goal of producing an energetic accelerated GCIB for workpiece processing. The extension tube **402** has a length L_E and serves to prevent positive ions formed in the ionizer from being extracted backward through the ionizer's inlet end by the high potential difference between ionizer **400** and the skimmer aperture (**120, Fig. 13**). The extension tube **403** is at ionizer potential (V_{Acc}) and shields ions within the ionizer **400**

10   from effects of external electrical fields in the upstream direction. Support plate **410** is referenced in the discussion of **Figure 7** below.

Figure 6 presents a cut-away section **450** of the improved ionizer **400** shown in **Fig. 5**. The cut is made along cutting plane **B—B**, as shown in **Fig. 5**. A partial cylindrical array of thin

15   rod anode electrodes **452** (three of fifteen indicated, for example) is supported and electrically connected by support plate **454**. An electrical connection terminal **456** permits electrical connection for biasing support plate **454** and thin rod anode electrodes **452**. The partial cylindrical array of thin rod anode electrodes **452** is substantially concentric with gas-cluster jet axis (**129 in Fig. 5**). A partial cylindrical array of thin rod electron-repeller

20   electrodes **458** (three of thirteen indicated, for example) are supported and electrically connected by support plate **460**. The partial cylindrical array of thin rod electron-repeller electrodes **458** is substantially concentric with gas-cluster jet axis (**129 in Fig. 5**). An electrical connection terminal **462** permits electrical connection for biasing support plate **460** and thin rod anode electrodes **458**. A partial cylindrical array of thin rod ion-repeller

25   electrodes **464** (two of eleven indicated, for example) are supported and electrically connected by support plate **466**. The partial cylindrical array of thin rod ion-repeller electrodes **464** is substantially concentric with gas-cluster jet axis (**129 in Fig. 5**). An electrical connection terminal **468** permits electrical connection for biasing support plate **466** and thin rod anode electrodes **464**. A noble gas plasma electron source comprises plasma

30   chamber body **470**, plasma chamber **472**, thermionic filament **476**, noble gas entry aperture

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486, and multiple plasma source chamber extraction apertures **480** (one of seven indicated, for example). Two filament attachment clamps **478** (one of two shown in this cutaway view) provide electrical connection to thermionic filament **476**, which is preferably a tungsten pigtail filament having 1-1/2 turns in the pigtail (additional detail viewable in **Fig. 7.**) An
5   electron-acceleration electrode **488** has multiple apertures **482** (one of seven indicated, for example). An electron-deceleration electrode **490** has multiple apertures **484** (one of seven indicated, for example). Multiple apertures **484**, multiple apertures **482** and multiple apertures **480** are all aligned, from multiple plasma source chamber extraction apertures **480** through multiple apertures **482** through multiple apertures **484**.

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Figure 7 presents a sectional view of a portion **500** of the improved ionizer **400** shown in **Fig. 5**. The cut is made along cutting plane **B—B**, as shown in **Fig. 5**. This view shows that the ionizer **400** has a clear aperture with a radius R_0. In a preferred embodiment, R_0 is approximately 17mm. The radius of the partial cylindrical array of thin rod anode electrodes
15   **452** (three of fifteen indicated, for example) is R_1. In a preferred embodiment, R_1 is approximately 22mm. The radius of the partial cylindrical array of thin rod electron-repeller electrodes **458** (three of thirteen indicated, for example) is R_2. In a preferred embodiment, R_2 is approximately 33mm. The radius of the partial cylindrical array of thin rod ion-repeller electrodes **464** (two of eleven indicated, for example) is R_3. In a preferred embodiment, R_3 is
20   approximately 46mm. The active ionization region of the improved ionizer **400** is the substantially cylindrical volume defined by the radius R_0 and the length L of the distance between support plate **460** and the opposing support plate (**410, Fig. 5**) that supports the opposite end of the partial cylindrical array of thin rod electron-repeller electrodes **458**. In a preferred embodiment, L is approximately 2.8 R_0. Values of L greater than 1.8 R_0 can be
25   perform effectively. The length of the extension tube is L_E. In a preferred embodiment L_E is approximately 4 R_0. Values of L_E greater than about 2 R_0 provide significant benefit, with longer values of L_E generally providing greater effectiveness at reducing backward extraction of ions.

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Figure 8 provides a detailed representation of a configuration 550 of extraction apertures in the noble gas plasma electron source. Seven extraction apertures are arranged with six apertures 480 (one shown for example) approximately equally spaced on the circumference of a circle 552 of approximately 18 mm diameter and a seventh center aperture 554. Inset

5   556 shows additional details of the apertures 480. Inner diameter is approximately 3mm and exit diameter is approximately 5 mm. Corresponding apertures in electron acceleration electrode 488 are approximately 5.5 mm and corresponding apertures in electron deceleration electrode 490 are approximately 6 mm.

10   Figure 9 is a schematic of a portion 600 of the system illustrating details of biasing of the electrodes of improved ionizer 400. As shown, thermionic filament 476 is insulated from the plasma chamber body 470 by insulator 602. Noble gas is admitted to the plasma chamber 472 via noble gas entry aperture 486. An insulated gas feed tube 622 provides pressurized noble gas (preferably argon) to a remotely controllable gas valve 624 (preferably a mass flow

15   controller valve with fiber optic control input) that regulates the admission of low pressure gas to the plasma chamber 472 via gas feed tube 628 and noble gas entry aperture 486. The remotely controllable gas valve 624 is at the ionizer potential (approximately V_{Acc}) to avoid high voltage breakdown through low-pressure gas in gas feed tube 628. Insulated gas feed tube 622 contains only gas at a pressure greater than one atmosphere to prevent high voltage

20   discharge along the gas column to ground. A filament power supply 608 provides filament voltage V_F for driving current through thermionic filament 476 to stimulate thermoelectron emission. Filament power supply 608 controllably provides about 140 to 200 amps at 3 to 5 volts. An arc power supply 610 controllably provides arc voltage to bias the plasma chamber body 470 positive with respect to the thermionic filament 476. Arc power supply 610 is

25   typically operated at a fixed voltage V_A, typically about 35 volts, and provides a means for accelerating the electrons within the plasma chamber for forming a plasma. Filament current is controlled to regulate the arc current supplied by the arc power supply 610. Arc power supply 610 is capable of providing up to 5A arc current to the plasma arc. The arc in the plasma chamber 472 results in creation of argon plasma in the chamber. Electrons in the

30   argon plasma are extracted from the plasma chamber 472 and directed into the ionizer by an

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acceleration-deceleration extraction system. Electron deceleration electrode **490** is biased positively with respect to the plasma chamber body **470** by electron bias power supply **612**. Electron bias power supply **612** provides bias voltage V_B. V_B is controllably adjustable over the range of from 30 to 400 V. Electron acceleration electrode **488** is biased positively with

5   respect to electron deceleration electrode **490** by electron extraction power supply **616**. Electron extraction power supply **616** provides electron extraction voltage V_{EE}. V_{EE} is controllable in the range from 20 to 250 V. An acceleration power supply **620** supplies acceleration voltage V_{Acc} to bias thin rod anode electrodes **452** and electron deceleration electrode **490** and extension tube (**402, Fig. 5**) and exit electrode (**404, Fig. 5**) positive with

10   respect to earth ground. V_{Acc} is the acceleration potential for gas-cluster ions produced in ionizer **400** and is controllable and adjustable in the range from 1 to 80 kV. An electron repeller power supply **614** provides electron repeller bias voltage V_{ER} for biasing electron repeller electrodes **458** negative with respect to V_{Acc}. V_{ER} is controllable in the range of from 50 to 100 V. An ion repeller power supply **618** provides ion repeller bias voltage V_{IR} to bias

15   ion repeller electrodes **464** positive with respect to V_{Acc}. V_{IR} is controllable in the range of from 50 to 150 V. A fiber optics controller **630** receives electrical control signals on cable **634** and converts them to optical signals that are transmitted on fiber optics control link **632** to control components operating at high potentials using signals from a grounded control system. Fiber optics control link **632** conveys control signals to remotely controllable gas

20   valve **624**, to filament power supply **608**, to arc power supply **610**, to electron bias power supply **612**, to electron repeller power supply **614**, to electron extraction power supply **616**, and to ion repeller power supply **618**.

       Figure 10 is a schematic of a portion **640** of the system showing plasma formation and

25   electron extraction from the noble gas plasma electron source. Argon plasma **642** is generated in the plasma chamber (**472, Fig. 9**). Electrons **644** are extracted from the argon plasma **642** and injected into the active ionization region of improved ionizer **400**. As was previously discussed in relation to **Fig. 4**, electrostatically confined extracted electrons **644** orbit, eventually ionizing gas-clusters or striking thin rod anode electrodes **452** or electron

30   deceleration electrode **490**, where they produce large quantities of low energy secondary

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electrons. The secondary electrons help ensure that the newly-formed ionized cluster jet remains space-charge neutral by providing low energy electrons that can be attracted into the positively ionized gas-cluster jet as required to maintain neutrality. Since controllable gas valve 624 continuously admits low-pressure argon gas into the plasma chamber (472, Fig. 6)

5   via gas feed tube 628, there is a continuous flow of noble gas (preferably argon) out of the plasma chamber (472, Fig. 6) through multiple apertures 646 and the pressure in the plasma chamber (472, Fig. 6) is higher than that in the active region outside the plasma chamber (472, Fig. 6). This flow tends to reduce entry of reactive or corrosive gases evolved from the gas-cluster jet from entering the plasma chamber to react with the hot thermionic filament

10   (476, Fig. 9). Of course there is some back diffusion of reactive gas into the plasma chamber (472, Fig. 6) through multiple apertures 646, but the amount is so small that it has little practical effect. A small amount of tungsten can be expected to evaporate from thermionic filament (476, Fig. 9) and escape through multiple apertures 646 to contribute metallic contaminants to the process, but again, the amount is much smaller than in prior art ionizers

15   for GCIB. Since the interaction of reactive gases with the hot thermionic filament is limited and since all of the electrodes and their support plates can be fabricated from high purity graphite, the improved ionizer 400 offers little opportunity for generation of metallic contaminants as a result of interaction of reactive gases with the ionizer.

20   Figure 11 is a schematic of a portion 650 of a second preferred embodiment of the configuration of the extraction apertures 656 (one of six indicated), 658 (one of six indicated), and 668 (one of six indicated) in the plasma chamber body 662, in the electron acceleration electrode 654, and in the electron deceleration electrode 652, respectively. In this configuration, the center extraction aperture (554, Fig. 8) employed in the configuration

25   of Figure 8 has been omitted, leaving an extraction aperture pattern of only six extraction apertures. Note that at position 666 of deceleration electrode 652 there is no center aperture (as contrasted to Fig. 10). By omitting the center aperture, the solid angle for line-of-sight escape of evaporated tungsten from filament 476 is significantly reduced without a corresponding large reduction in the amount of electrons that can be extracted from the

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plasma electron source plasma chamber **664**. Accordingly, further reduction in metallic contamination from the ionizer is realized with only a small reduction in performance.

Figure 12 is a schematic of a portion **670** of a third preferred embodiment of the
5   configuration of the plasma chamber **678** and the extraction apertures **676** (one of seven indicated), **686** (one of seven indicated), and **684** (one of seven indicated) in the plasma chamber body **680**, in the electron acceleration electrode **674**, and in the electron deceleration electrode **672**, respectively. A noble gas entry aperture **682** facilitates introducing noble gas into the plasma chamber **678** for plasma formation. In this configuration, the extraction
10 aperture configuration is the same as previously shown in **Figure 8** including the center extraction aperture (**554, Fig. 8**). By rotating the plasma chamber body **680** relative to the position of plasma chamber body (**470, Fig. 10**), the location of the filament **476** is offset from the extraction apertures so that there is no direct line-of-site for escape of evaporated tungsten from filament **476**. Accordingly, further reduction in metallic contamination from
15 the ionizer is realized with no reduction in performance.

Figure 13 shows a schematic of the basic elements of a typical configuration for a GCIB processing apparatus **700** incorporating the improved ionizer **400** of the invention. The improved ionizer **400** is disposed so as to lie along and to surround the gas-cluster jet axis
20 **129** by electrically insulating support **408** so that after passing through the skimmer aperture **120**, the supersonic gas jet **118** enters the extension tube **402** of the improved ionizer **400**. Within improved ionizer **400**, gas clusters in the supersonic gas jet are ionized by electron impact ionization and the resulting GCIB **128** is maintained substantially space-charge neutral. Accelerator power supply **620** provides acceleration voltage V_{Acc} to provide GCIB
25 acceleration and is controllably adjustable over the range of from 1 to 80 kV. Suppressor power supply **720** provides suppressor voltage V_S to suppressor electrode **142** to extract gas-cluster ions from the improved ionizer **400**, to focus the GCIB **128**, and to prevent downstream electrons from back-streaming and loading the accelerator power supply **620**. V_S is controllably adjustable over the range of from 0 to 50 kV. Gas-cluster ions are

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extracted from ionizer **400** by the strong electric field created between exit electrode **404** and suppressor electrode **142**. Filament power supply **608**, arc power supply **610**, electron bias power supply **612**, electron repeller power supply **614**, electron extraction power supply **616**, and ion repeller power supply **618**, provide bias voltages and power currents to improved

5   ionizer **400** through electrical cable **710**, according to principals previously described in the discussion of **Figure 9**. A system controller **702** provides control signals to coordinate and control controller **220** via cable **712**, suppressor power supply **720** via cable **714**, accelerator power supply **620** via cable **716** and fiber optics controller **630** via cable **634**. Fiber optics controller **630** converts electrical control signals received on cable **634** to optical signals that

10 are transmitted on fiber optics control link **632** to control remotely controllable gas valve **624**, to filament power supply **608**, to arc power supply **610**, to electron bias power supply **612**, to electron repeller power supply **614**, to electron extraction power supply **616**, and to ion repeller power supply **618**. A gas bottle **704** contains a pressurized noble gas **706**, preferably argon. A pressure regulator **718** regulates the pressure of the noble gas to a value

15 approximately in the range of from one to two atmospheres. An insulated gas feed tube **622** conducts pressure regulated gas from the pressure regulator **718** at ground potential to the remotely controllable gas valve **624** at ionizer potential (approximately V_{Acc}). The remotely controllable gas valve **624** controls the low-pressure flow of gas into the plasma chamber **472** of the improved ionizer **400**. Low-pressure noble gas flows from remotely controllable gas

20 valve **624** through gas line **628** via insulated feed-through **708** into the plasma chamber **472**. The GCIB **128** controllably processes workpiece **152** without contributing an undesirably high level of metallic and particulate contamination to the workpiece **152**.

Figure 14 is a graph showing improvement in reduction of metals contamination in

25 semiconductor processing due to the improved ionizer of the invention. The graph compares the performance of the prior art ionizer of **Figure 2** (left bar, labeled S.N.), the improved ionizer of the present invention of **Figures 3** and **4** (middle bar, labeled Reflex) and the further improved ionizer **400** of the present invention (right bar, labeled PEG) in terms of metals contamination on a surface of a semiconductor wafer GCIB-processed with reactive

30 etchant gas-cluster ions. All wafers received a GCIB processing dose of 1 x 10^{15} gas-cluster

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ions/cm^2 with the indicated corrosive source gas mixture. The data for the self-neutralizing
ionizer of **Fig. 2** (shown in left bar) was obtained by TXRF measurement, while Vapor Phase
Decomposition – Inductively Coupled Plasma Mass Spectrometry (VPD ICPMS) was used
for measurement the improved ionizer of **Figures 3** and **4** (middle bar) and for the improved

5   ionizer **400** of the invention (right bar), utilizing the seven aperture electron extraction
configuration of **Figure 8**. The reduction in metallic contamination with the improved
ionizer **400** of the invention is striking. With improved ionizer **400**, metals performance with
less corrosive gases mixtures is the same or better than that with O_2-NF_3. Although not
readily apparent from **Fig. 14**, a considerable reduction in tungsten contamination occurs

10 with the improved ionizer **400** of the present invention, indicating that the corrosive gases are
not attacking the filament within the plasma chamber. Life tests were run using improved
ionizer **400** with 5%NF_3 in oxygen for 400 hours and with 5%GeH_4 in argon for 350 hours.
In both cases the source continued to run normally after test. In each case, after testing the
ionizer was shut down to evaluate wear and no significant wear was evident on the filament

15 or the plasma chamber.

Although **Figures 5, 6, 7, 9, 10, 11, 12,** and **13** have illustrated ionizers having a single
plasma electron source (possibly having multiple apertures) for supplying ionizing electrons,
it will be easily appreciated by those skilled in the art, that ionizers within the scope and spirit

20 of the invention can be constructed having two or more plasma electron sources for providing
electrons to the ionizing region in order to facilitate providing larger quantities of ionizing
electrons to the ionizing region of the ionizer. Although the invention has been described
with respect to various embodiments, it should be realized this invention is also capable of a
wide variety of further and other embodiments within the spirit of the invention.

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It is claimed:

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1.   An ionizer for forming a gas-cluster ion beam, comprising:

an inlet end and an outlet end partially defining an ionization region through

which a gas-cluster jet comprised of gas-clusters is directed along an

axis, from the inlet end to the outlet end; and

at least one plasma electron source for providing electrons to the ionizing

region, the electrons for ionizing at least a portion of the gas-clusters to

form a gas-cluster ion beam.

2.   The ionizer of claim 1, further comprising a first set of substantially linear rod
electrodes disposed substantially parallel to and in a partial, substantially cylindrical
pattern about the gas-cluster jet axis, further defining the ionization region.

3.   The ionizer of claim 2, wherein the first set of rod electrodes are anode electrodes
disposed in a partial, substantially cylindrical pattern that is substantially concentric
with the gas-cluster jet axis, the pattern having a radius R_1.

4.   The ionizer of claim 3, further comprising a second set of substantially linear rod
electrodes disposed substantially parallel to and in a partial, substantially concentric
cylindrical pattern about the gas-cluster jet axis, the pattern having a radius R_2,
wherein R_2 is greater than R_1.

5.   The ionizer of claim 4, further comprising a third set of substantially linear rod
electrodes disposed substantially parallel to in a partial, substantially concentric
cylindrical pattern about the gas-cluster jet axis, the pattern having a radius R_3,
wherein R_3 is greater than R_2.

6.   The ionizer of claim 5, wherein:
the second set of substantially linear rod electrodes are electrically biased to
act as electron-repeller electrodes; and

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the third set of substantially linear rod electrodes are electrically biased to act as ion-repeller electrodes.

7.   The ionizer of claim 3, wherein at least one electrode of the first set of rod electrodes, and the second set of rod electrodes comprises graphite.

8.   The ionizer of claim 3, wherein:

the ionization region is defined to be substantially cylindrical, having a clear aperture of radius R_0, wherein R_0 is less than R_1; and

the ionization region has a length L, wherein L is greater than or equal to about 1.8 R_0.

9.   The ionizer of claim 1, wherein:

the ionization region is defined to be substantially cylindrical, having a clear aperture of radius R_0; and

the inlet end comprises an extension tube for reducing the extraction of positive ions through the inlet end.

10.   The ionizer of claim 9, wherein the extension tube is of a length greater than or equal to about 2 R_0.

11.   The ionizer of claim 1, wherein the at least one plasma electron source comprises a plasma chamber body defining a plasma chamber and including one or more apertures through which electrons are provided to the ionization region for at least partially ionizing the gas-cluster jet by electron-impact ionization.

12.   The ionizer of claim 11, wherein the plasma chamber contains a plasma of a noble gas.

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13.   The ionizer of claim 11, wherein the at least one plasma electron source further
       comprises:

              a heated thermionic filament within the plasma chamber for emitting

                     electrons;

              an aperture for introducing a noble gas into the plasma chamber;

              means for accelerating the electrons to generate a plasma of said noble gas

                     within the plasma chamber;

              an acceleration-deceleration electrode; and

              a biasing means for extracting electrons from the plasma in the plasma

                     chamber into the ionization region.

14.   The ionizer of claim 13, wherein:

              the thermionic filament is a metal filament that evaporates undesired metal

                     vapor;

                     and

              the one or more apertures in the plasma chamber body are arranged to reduce

                     the transmission of evaporated metal into the ionization region.

15.   The ionizer of claim 13, wherein the thermionic filament is a metal filament that
       evaporates undesired metal vapor and is disposed within the plasma chamber such
       that no direct line-of-sight path from the thermionic filament into the ionization
       region exists.

16.   A gas-cluster ion beam processing apparatus for processing a workpiece by gas-
       cluster ion beam irradiation, comprising:

              a reduced-pressure atmosphere enclosure;

              a nozzle within the enclosure for forming a gas-cluster jet comprising a

                     plurality of gas-clusters;

              an ionizer within the enclosure for ionizing at least a portion of the gas-

                     clusters in the gas-cluster jet to form a gas-cluster ion beam, the ionizer

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comprising:

an inlet end and an outlet end defining an ionization region

through which a gas-cluster jet comprised of gas-

clusters is directed along an axis, from the inlet end to

the outlet end; and

at least one plasma electron source for providing electrons to

the ionizing region, the electrons for ionizing at least a

portion of the gas-clusters to form a gas-cluster ion

beam;

acceleration means within the enclosure for accelerating said gas-

cluster ion beam; and

means for positioning a workpiece within the enclosure for irradiation

by the accelerated gas-cluster ion beam.

17. A method for forming a gas-cluster ion beam comprising the steps of:

providing a reduced pressure atmosphere enclosure;

generating a gas-cluster jet comprised of a plurality of gas-clusters within the

reduced-pressure atmosphere;

providing an ionization region within the reduced pressure atmosphere;

directing the gas-cluster jet through the ionization region;

providing at least one plasma electron source near the ionization region;

directing electrons from the at least one plasma electron source into the

ionization region to ionize at least a portion of the gas-clusters in the

gas-cluster jet to form a gas-cluster ion beam.
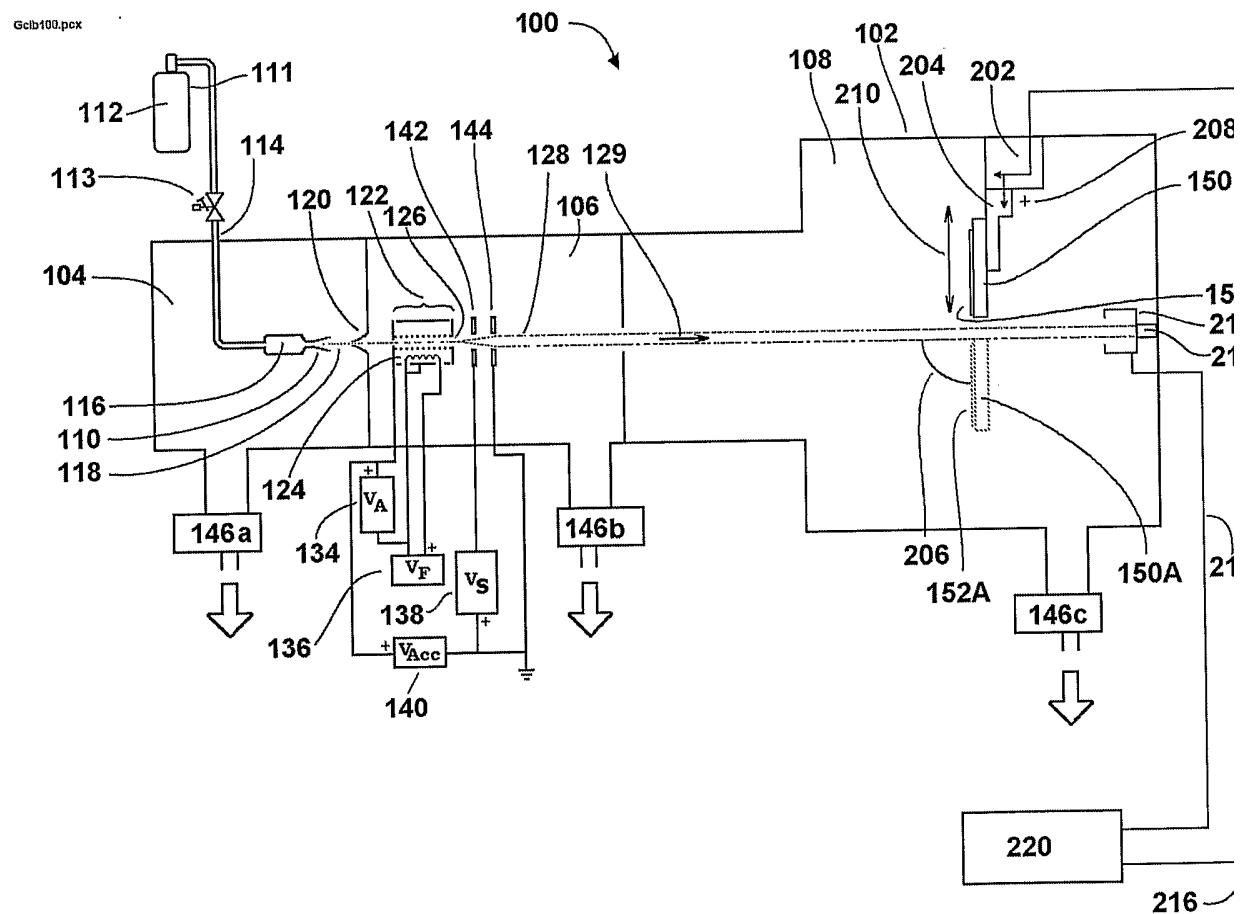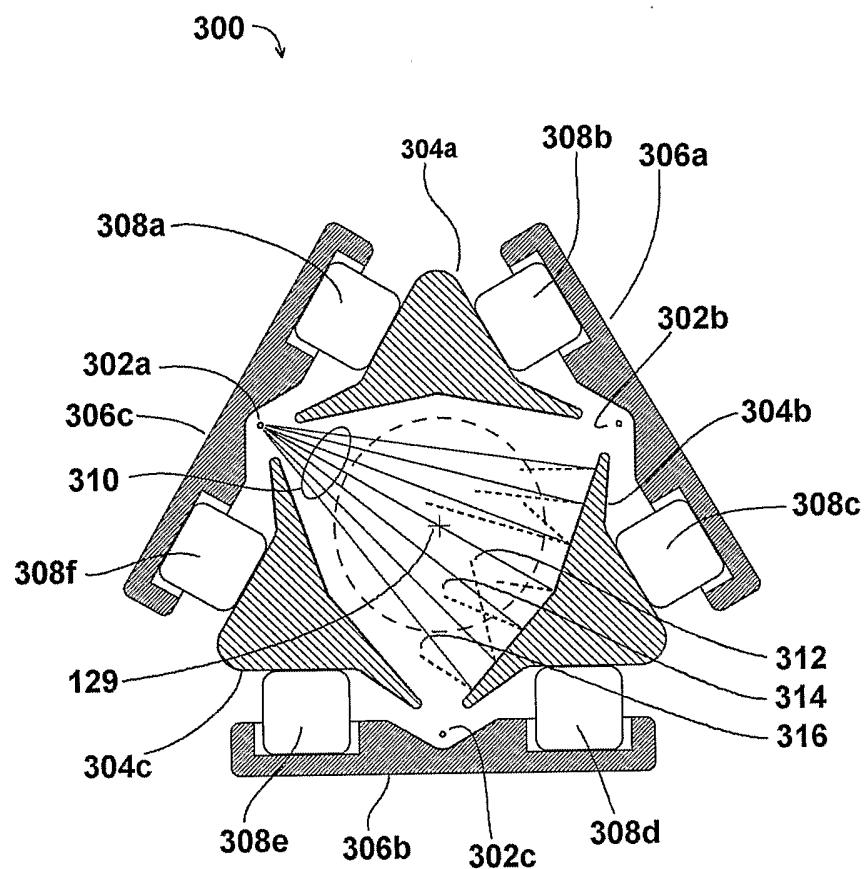
Figure 1 Prior Art

Figure 2 Prior Art

Figure 3

Figure 4

400

B

B

404

402

129

129

A

406

A

410

408

Figure 5

Figure 6

500

400

452 **462** **490** **488**

456

464

458

468

129

470
472
486

476
478
480

408
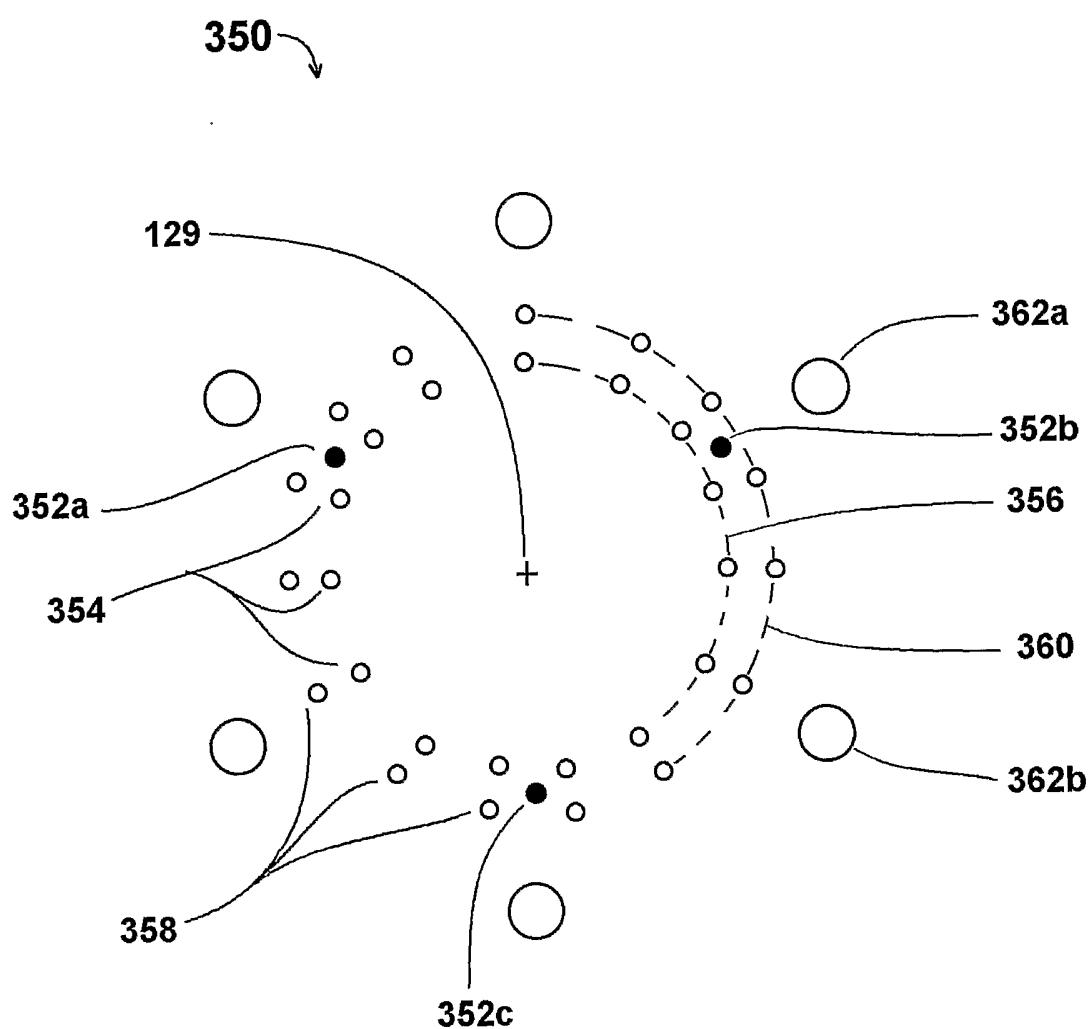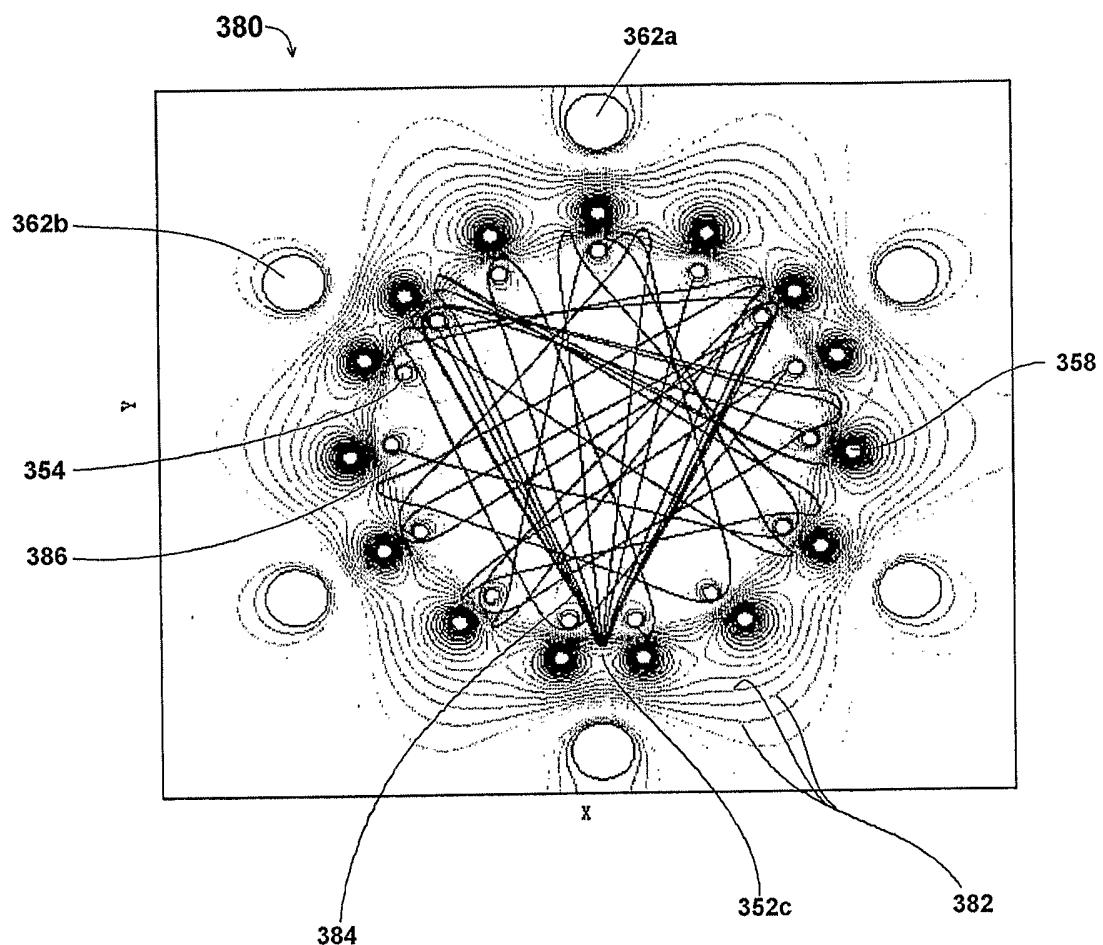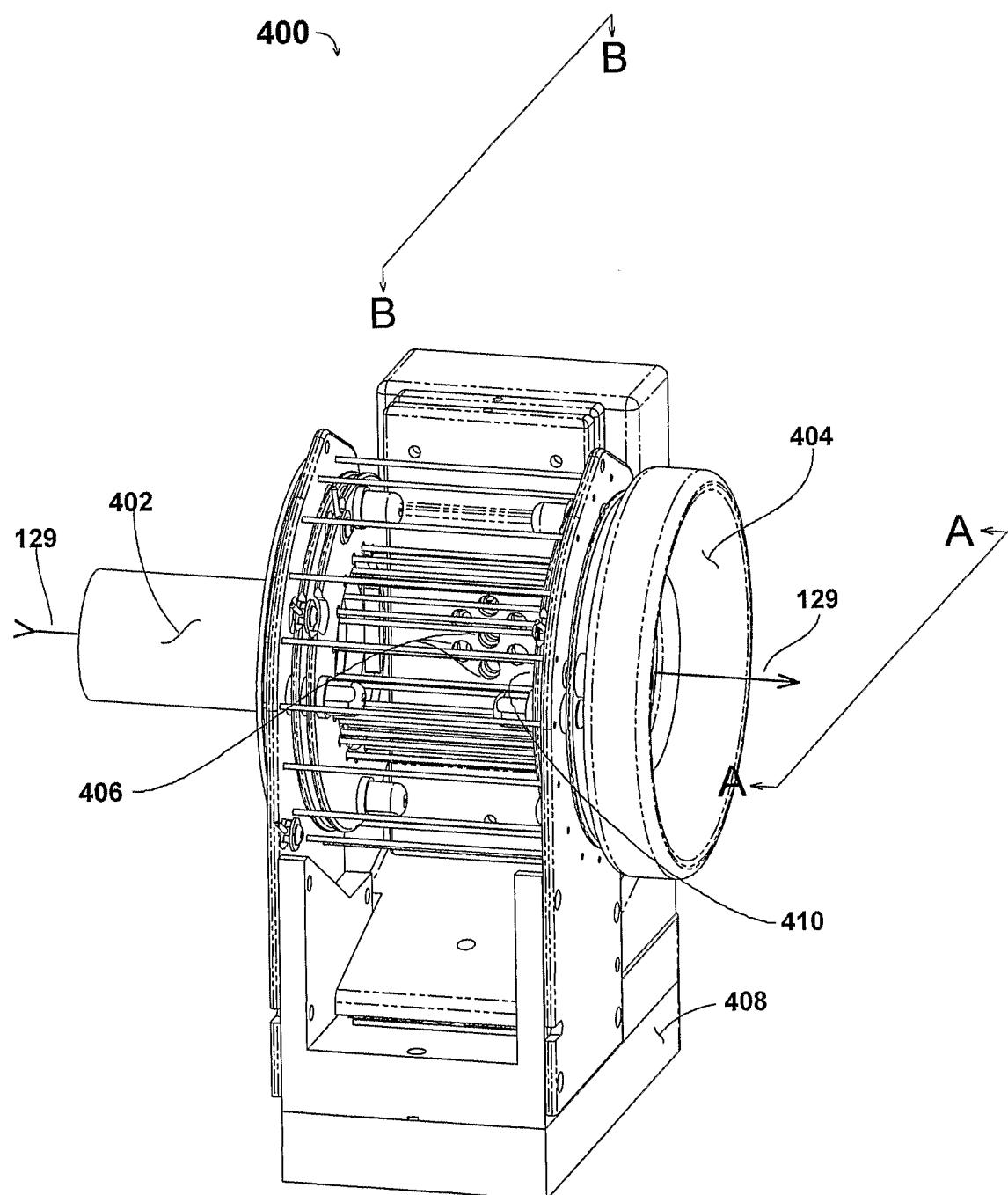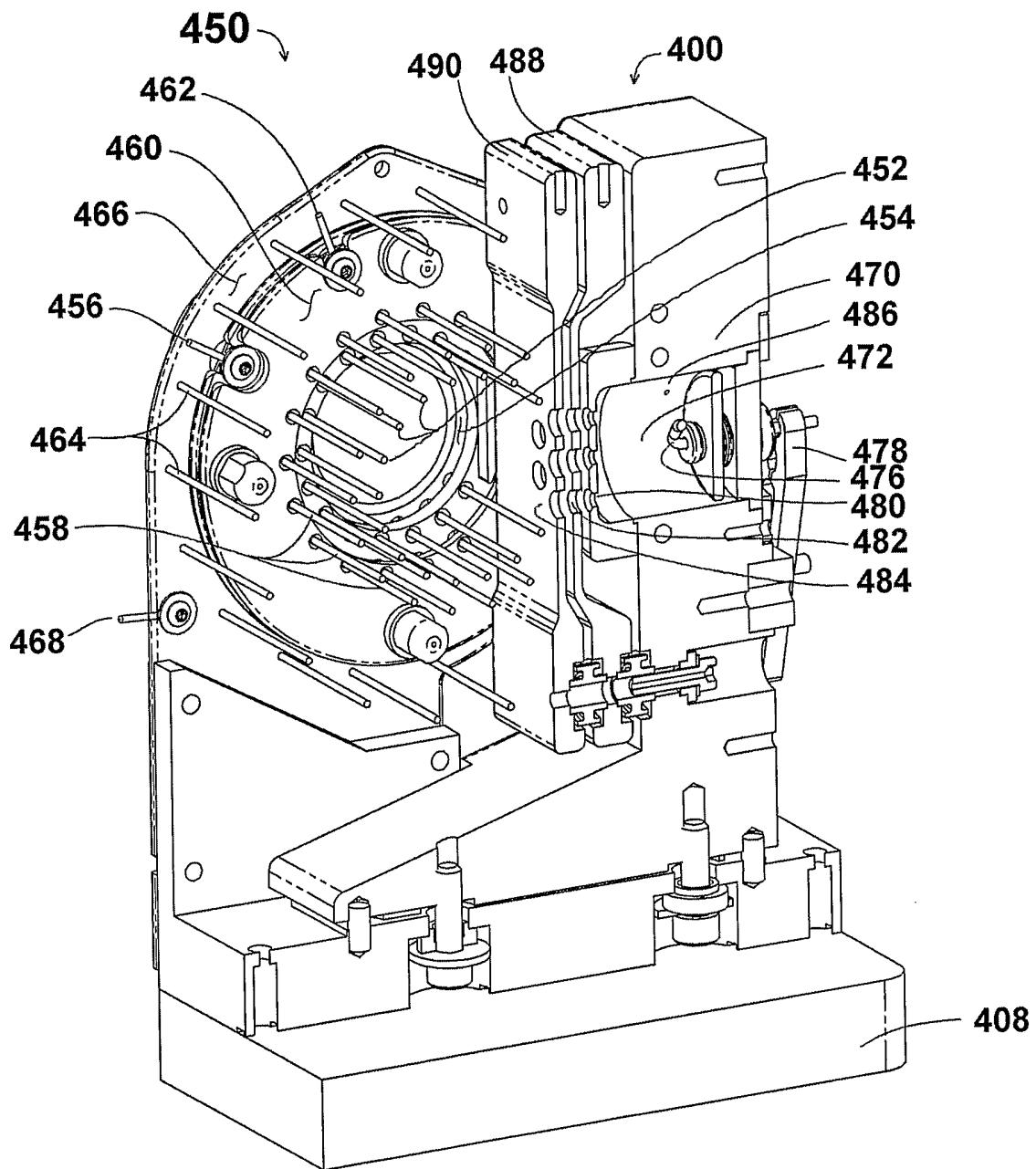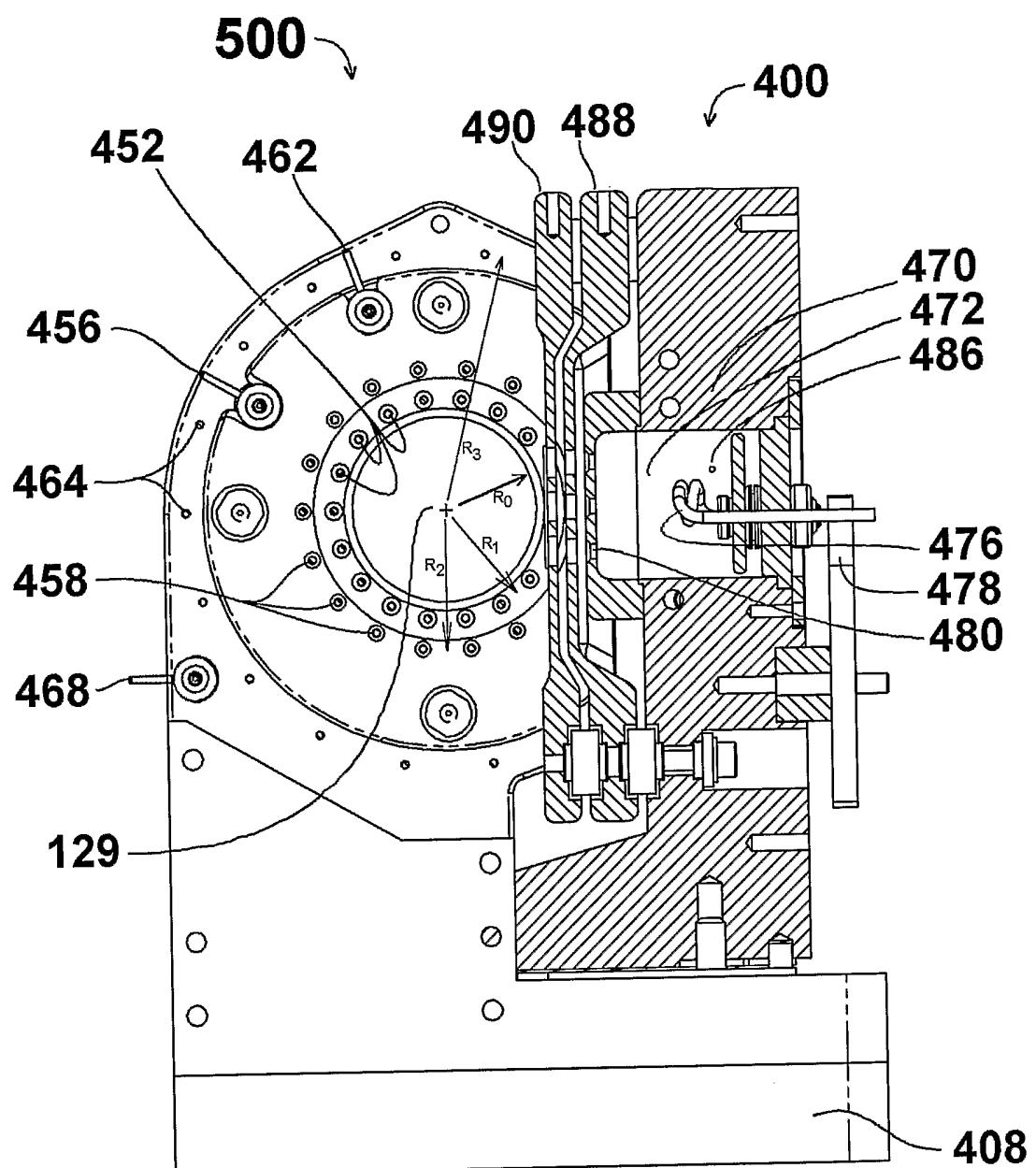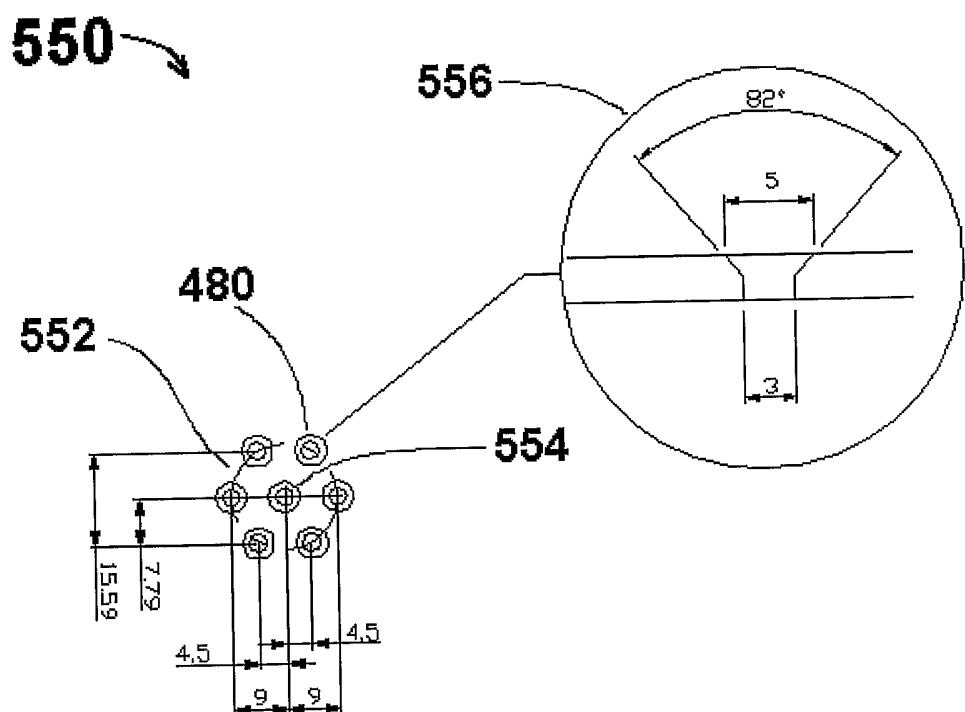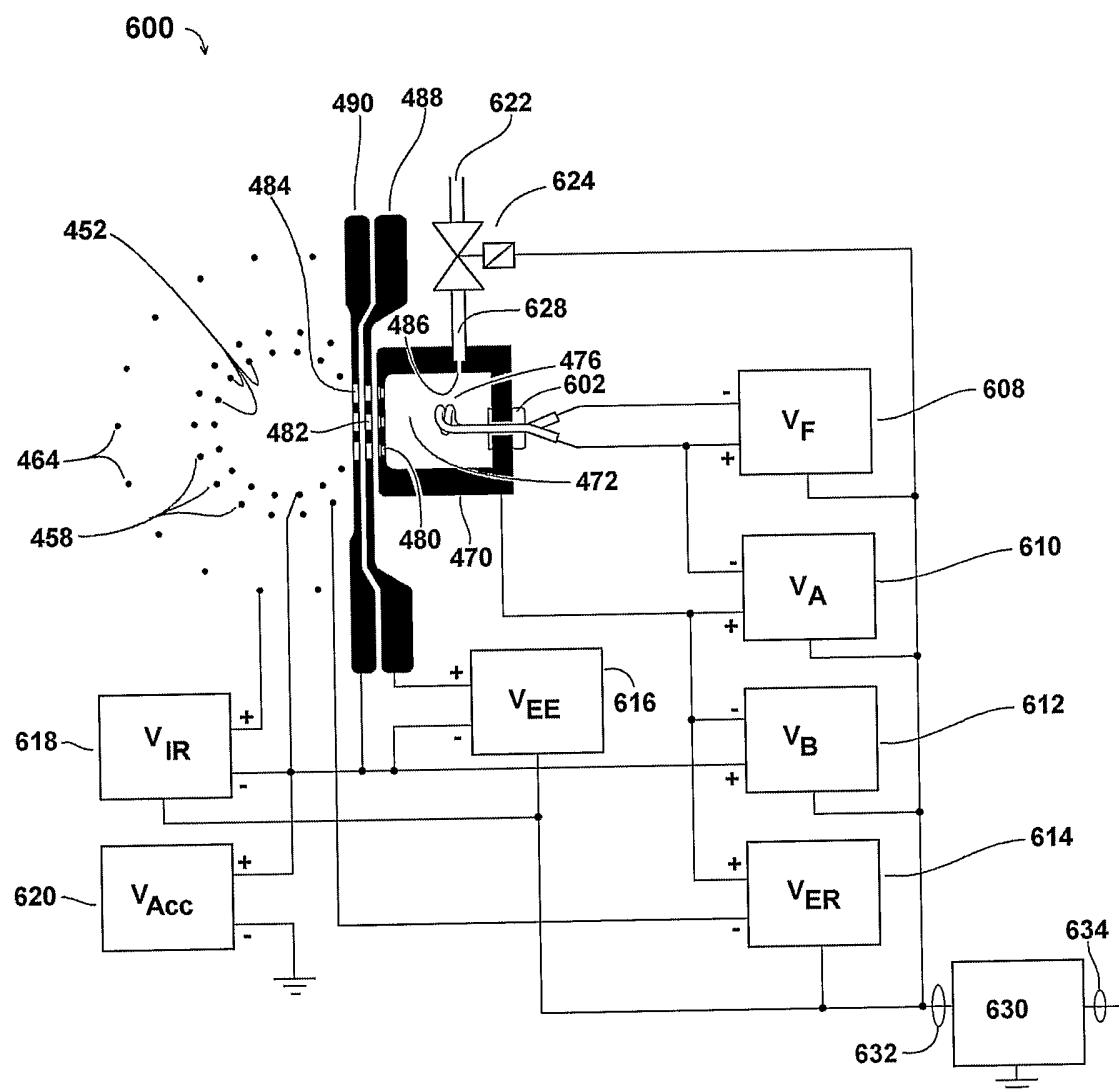
Figure 7

Figure 8

Figure 9

Figure 10

Figure 11

670

452

672   674

676

678
680

464

682

458

476

602

686   684
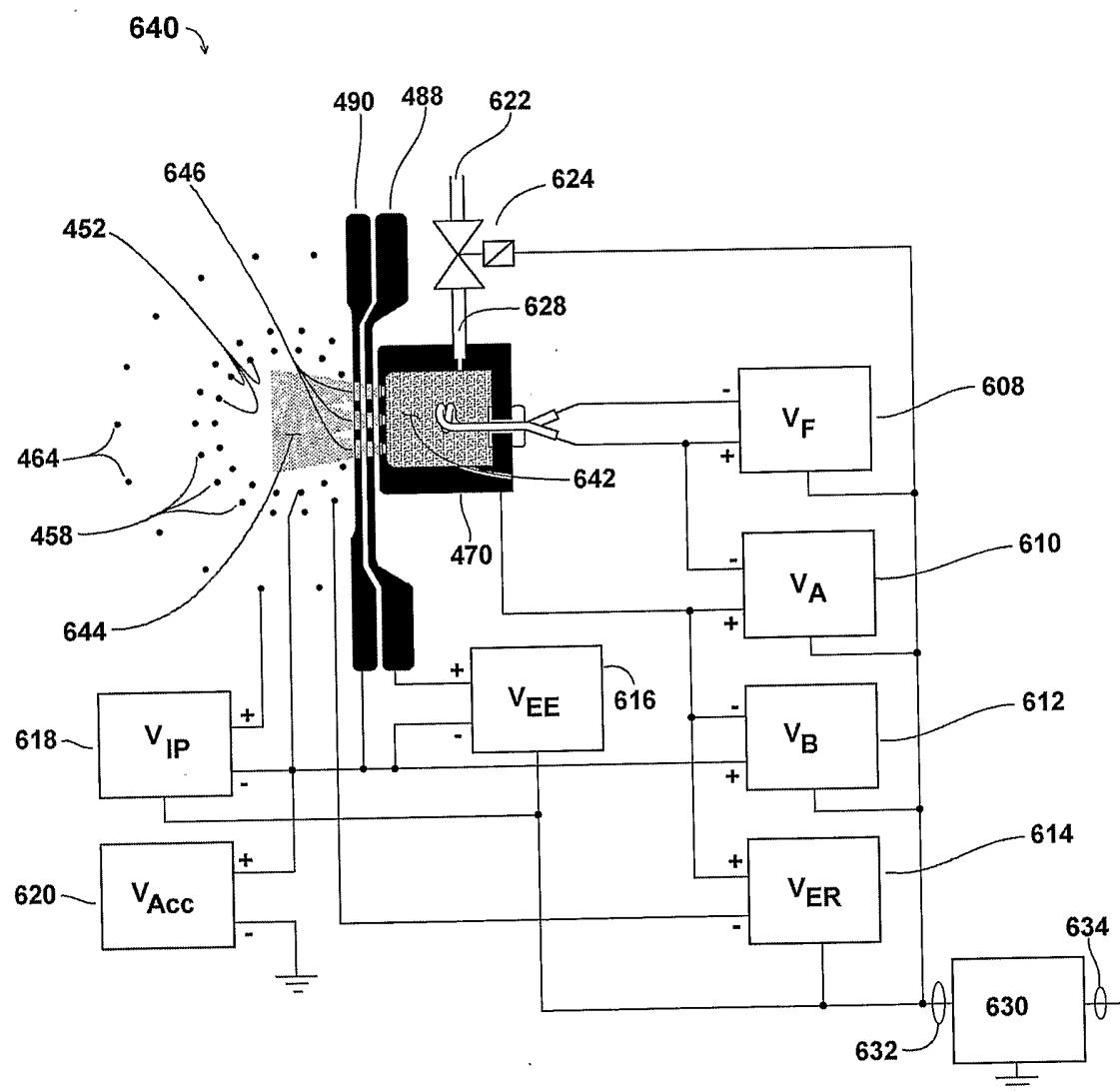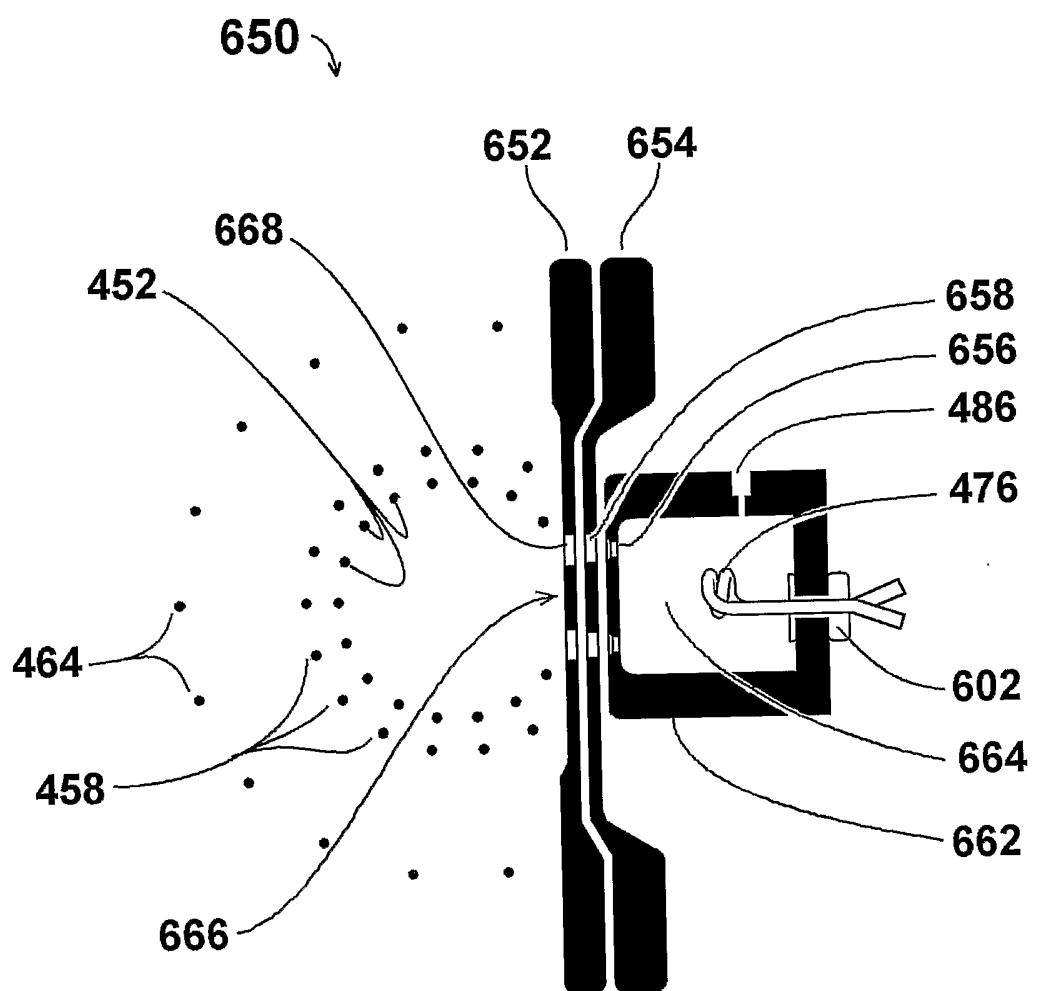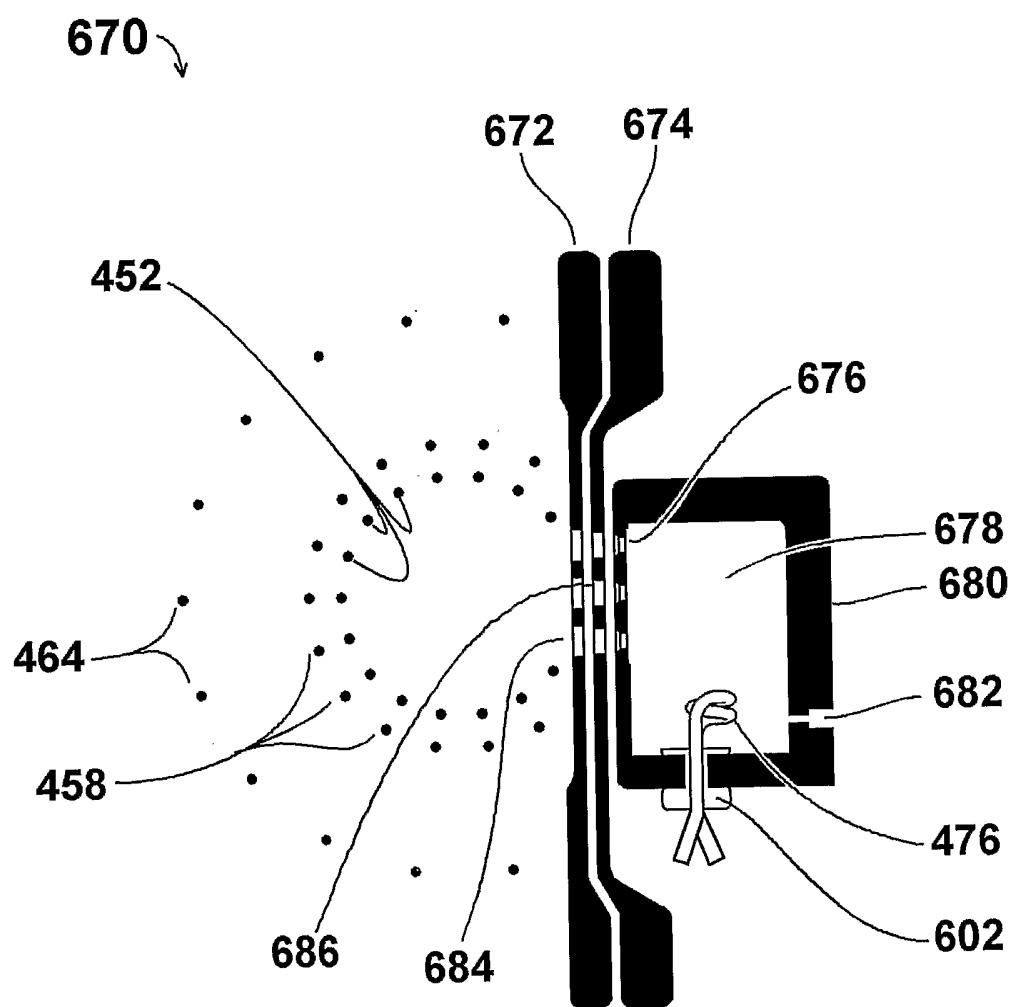
Figure 12

Figure 13

Figure 14