(54) Title: METHOD AND APPARATUS FOR IMPROVED PROCESSING WITH A GAS-CLUSTER ION BEAM
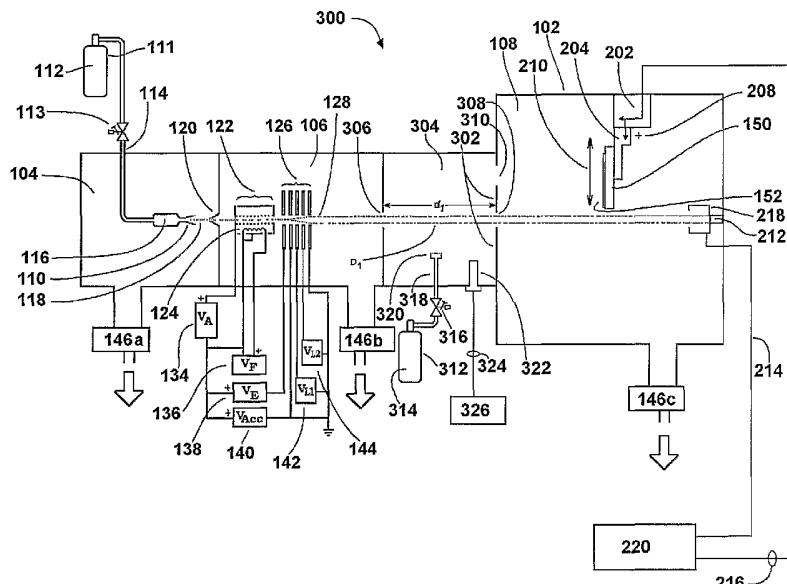
(57) Abstract: Apparatus and methods for improving processing of workpieces with gas-cluster ion beams and modifying the gas-
cluster ion energy distribution in the GCIB. In a reduced-pressure environment, generating an energetic gas-cluster ion beam and
subjecting the beam to increased pressure region.

Method and Apparatus for Improved Processing with a
Gas-Cluster Ion Beam

Field of the Invention

5   This invention relates generally to methods and apparatus for processing surfaces with a gas-cluster ion beam and, more particularly, to methods and apparatus for modifying characteristics of a gas-cluster ion beam to achieve improved surface processing results.

Background of the Invention

The use of a cluster ion beam for processing surfaces is known (see for example, US patent

10   5,814,194, Deguchi *et al.*) in the art. As the term is used herein, gas-clusters refer to nano-sized aggregates of materials that are gaseous under conditions of standard temperature and pressure.   Such gas-clusters are typically comprised of aggregates of from a few to several thousand molecules loosely bound to form the cluster. The clusters can be ionized by electron bombardment or other means, permitting them to be formed into directed beams of

15   controllable energy. Such ions each typically carry positive charges of $q \cdot e$ (where e is the electronic charge and q is an integer of from one to several representing the charge state of the cluster ion). Non-ionized clusters may also exist within a cluster ion beam. 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

20   impact, with each individual molecule carrying only a small fraction of the total cluster ion energy. Consequently, the impact effects of large cluster ions are substantial, but are limited to a very shallow surface region. This makes cluster ions effective for a variety of surface modification processes, without the tendency to produce deeper subsurface damage characteristic of conventional monomer ion beam processing.

25   Means for creation of and acceleration of such GCIBs are described in the reference (US 5,814,194) previously cited, the contents of which are incorporated by reference as though set out at length herein. Presently available cluster ion sources produce clusters ions having a

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wide distribution of sizes, N (where N = the number of molecules in each cluster ion - in the case of monatomic gases like argon, an atom of the monatomic gas will be referred to as a molecule and an ionized atom of such a monatomic gas will be referred to herein as a molecular ion or simply a monomer ion.)

5   Many useful surface processing effects can be achieved by bombarding surfaces with GCIBs. These processing effects include, but are not necessarily limited to, cleaning, smoothing, etching, doping, and film formation or growth. In many cases, it is found that in order to achieve industrially practical throughputs with GCIB processing, GCIB currents on the order of hundreds to thousands of microamps are required. Efforts to increase the intensity and

10   ionization of a GCIB beam tend to produce additional higher charge state clusters ($q > 1$). When ionization is performed by electron bombardment, ionization is produced by random electron impacts. In order to produce a high ratio of ionized to non-ionized clusters, the electron impact probability must be high and the resulting charge state distribution follows approximately Poisson statistics, with the approximate probability, P(q), of charge state q

15   given by:

$$P(q) = \frac{\overline{q}^{q}}{q!} e^{-\overline{q}}$$
                                   (Eqn. 1)

where $\overline{q}$ is the average ionized cluster charge state after leaving the ionizer. Thus, an ionized cluster beam with a highly ionized fraction will also include multiply-charged cluster ions in

20   the beam. For example, theoretically the average cluster charge state of a GCIB beam where 95% of the clusters are ionized would be 3, with more than 8% of the beam in charge states 6 and higher. However, such highly charged clusters can fragment, or undergo charge exchange reactions, or partially evaporate, resulting in a different charge state distribution and/or a different energy distribution, and so in a practical beam, the precise charge state and energy

25   distributions are not readily predicted.

In the prior art, it has been understood that optimal ion beam propagation is generally achieved under low-pressure conditions. It has also been understood that the moderate to high intensity GCIBs, as are normally required for efficient surface processing of materials on

an industrially economic scale, transport substantial quantities of gas in the form of gas-cluster ions to the target region. When gas-cluster ions in a GCIB reach the target, the clusters disintegrate and the GCIB-transported mass is released as molecular gas. The entire gas load of the beam is released when the GCIB strikes the target region. For an argon beam having a

5   beam current, I_B, the gas flow, F (sccm), transmitted in the beam is:

$$F = 2.23 \times 10^{-18} \left(\frac{N}{q}\right)\left(\frac{I_B}{e}\right) \qquad \text{(Eqn. 2)}$$

Accordingly, for a beam current of only 400μA and an N/q ratio of 5000, the beam transmits a substantial gas flow of about 27 sccm. In a typical GCIB processing tool, multiple large capacity vacuum pumps are employed in order to maintain a low-pressure environment in the

10   face of this gas load.

Because high intensity GCIBs contain clusters of various charge states, acceleration of such beams by applying an accelerating potential, V_{Acc}, of a few kV results in beams having clusters of multiple energies, $q \cdot V_{Acc}$ for all values of q present in the beam. In general, it has been learned that many of the beneficial processing effects that can be obtained by the use of

15   GCIB for processing workpiece surfaces are dependent on the energies of the gas-cluster ions in the beam. Etching of a surface, for example, generally proceeds faster by using higher energy clusters. Another valuable application of GCIB processing is the smoothing of surfaces, and GCIB has been shown to be in some cases superior to other methods for smoothing surfaces at the atomic or near-atomic scale. Although for some beam conditions

20   GCIB processing of a surface can produce exceptional smoothness, it has been observed that GCIB processing does not always smooth a surface. In fact, when the starting surface is relatively smooth, GCIB processing may, in some circumstances, roughen the surface. Often it is desirable to both etch and smooth a surface. When using conventional techniques to optimize processing conditions (for example, by selecting cluster source gas material, by

25   selecting acceleration potential, by selecting a GCIB current, and/or by selecting a GCIB processing dose) it has been found that frequently there is not a GCIB beam condition that gives an adequate etching rate while simultaneously smoothing, or at least not roughening, an already smooth surface. It has been found that an aggressive etch rate by GCIB processing

commonly requires high energy, high intensity GCIB conditions, while freedom from roughening and surface smoothing are best obtained with low energy beams (or with conditions that are otherwise not practical for etching). In such cases it has been necessary to use a combination of several GCIB steps to achieve a result approaching a desired objective.

5   Such a process would involve first an aggressive etch with a first set of beam conditions, followed by a second less aggressive etch using a second set of beam conditions to reduce the roughening caused by the first etch, and then yet another step that applies a beam condition that smoothes without any significant etching. Such combinations of steps or even more complex combinations are known in the art and result in complex processing recipes with low

10   throughputs for certain important processes, while sometimes still not achieving desired final results. US Patent No. 6,375,790 to Fenner, for example, teaches a GCIB processing apparatus adapted for multi-step processing of substrates capable of such complex processing recipes.

It is the case that the available ionizers for producing ionized gas-clusters for GCIB formation

15   inherently produce beams with a wide range of ionization states, and particularly including multi-ionized gas-clusters when operated at conditions that produce intense beams (see Eqn. 1 above) needed for high throughput GCIB processing of workpieces. When such beams are accelerated with potentials adequate to give energies that provide good etching rates, they tend to produce less-than-desirable surface smoothing and may even produce surface

20   roughening. This problem can be at least partially alleviated by complex or multi-step GCIB processing recipes that reduce processing throughput below desirable rates. However, sometimes even complex processing recipes with several different beam conditions do not produce the desired ultimate level smoothness needed for some important processes.

Summary of the Invention

25   In light of the deficiencies described above, it is an objective of this invention to provide a method of modifying GCIB characteristics to form a beam that has good smoothing capabilities and yet retains good etching capabilities.

It is another objective of this invention to provide a method of modifying GCIB characteristics to form a beam that has improved surface smoothing capabilities.

It is a further objective of this invention to provide an apparatus for modifying characteristics of a GCIB for workpiece processing such that the apparatus produces a GCIB capable simultaneously capable of high etching rate and good ultimate workpiece smoothness.

It is a still further objective of this invention to provide an apparatus for modifying characteristics of a GCIB for workpiece processing such that the apparatus produces a GCIB that has improved surface smoothing capabilities.

These and other objectives are achieved in the present invention through controlled variations in the environmental pressures and geometries employed during the formation of the GCIB.

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 figures and detailed description, wherein:

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

Figure 2 shows a schematic of a GCIB processing apparatus **300** according to an embodiment of the present invention;

Figure 3 is a schematic of a GCIB processing apparatus **350** according to a second embodiment of the present invention;

Figure 4 is a schematic of a GCIB processing apparatus **400** according to a third embodiment of the present invention;

Figure 5 is a graph showing results from measurement of GCIB characteristics after passing through a pressure cell under several pressure cell conditions;

Figure 6 is a graph showing dependence of GCIB etching rate on PDI (pressure-distance integral) value; and

Figure 7 is a graph showing dependence of final (end of process) surface roughness on PDI value, as measured by atomic force microscope.

Detailed Description of Preferred Embodiments of the Invention

Figure 1 shows a schematic of the basic elements of a typical 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

5   **104**, an ionization/acceleration chamber **106**, and a processing chamber **108**. The three chambers are evacuated to suitable operating pressures by vacuum pumping systems **146a**, **146b**, and **146c**, respectively. A condensable source gas **112** (for example argon or N_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

10 pressure vacuum through a properly shaped nozzle **110**. A supersonic gas-jet **118** results. Cooling, which results from the 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

15 downstream regions where such higher pressures would be detrimental (e.g., ionizer **122**, high voltage electrodes **126**, and processing chamber **108**). Suitable condensable source gases **112** include, but are not necessarily limited to argon, nitrogen, carbon dioxide, oxygen, and other gases and/or gas mixtures.

After the supersonic gas-jet **118** containing gas-clusters has been formed, the clusters are

20 ionized in an ionizer **122**. The ionizer **122** is typically an electron impact ionizer that 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 impact ejects electrons from the clusters, causing a portion the clusters to become positively ionized. Some clusters may have more

25 than one electron ejected and may become multiply ionized. A set of suitably biased high voltage electrodes **126** extracts the cluster ions from the ionizer, forming a beam, and then accelerates them to a desired energy (typically with acceleration potentials of from several hundred V to 100 of kV or higher) and focuses them to form a GCIB **128**. Filament power supply **136** provides filament voltage V_f to heat the ionizer filament **124**. Anode power

supply **134** provides anode voltage V_A to accelerate thermoelectrons emitted from filament **124** to cause them to irradiate the cluster containing gas-jet **118** to produce ions. Extraction power supply **138** provides extraction voltage V_E to bias a high voltage electrode to extract ions from the ionizing region of ionizer **122** and to form a GCIB **128**. Accelerator power

5   supply **140** provides acceleration voltage V_{Acc} to bias a high voltage electrode with respect to the ionizer **122** so as to result in a total GCIB acceleration potential equal to V_{Acc}. One or more lens power supplies (**142** and **144** shown for example) may be provided to bias high voltage electrodes with focusing voltages (V_{L1} and V_{L2} for example) to focus the GCIB **128**.

A workpiece **152**, which may be a semiconductor wafer or other workpiece to be processed

10   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 the GCIB **128** across large areas to produce spatially homogeneous results.

The GCIB **128** is stationary, has a GCIB axis **129**, and the workpiece **152** is mechanically

15   scanned through the GCIB **128** to distribute the effects of the GCIB **128** over a surface of the workpiece **152**.

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**,

20   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

25   respect to the axis of the GCIB **128** so that the GCIB **128** has an angle of beam incidence **206** with respect to the 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 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

5   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
cup or the like, closed except for a beam-entry opening, and is typically affixed to the wall of

10   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
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

15   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
removing the workpiece 152 from the GCIB 128 when a predetermined desired dose has been
delivered.

20   **Figure 2** shows a schematic of a GCIB processing apparatus 300 according to an
embodiment of the present invention. A baffle 302 (multiple baffles may be used, but a
single-baffle embodiment will be described for example and simplicity) creates a separate
pressure chamber 304 that can be pressurized to a higher pressure than the pressure in the
ionizing/acceleration chamber 106 and higher than the pressure in the processing chamber 108.

25   The ionizing/acceleration chamber 106 has an ionizing/acceleration chamber aperture 306
through which the GCIB 128 enters the pressure chamber 304. Baffle 302 has a pressure
chamber aperture 308 through which the GCIB 128 exits the pressure chamber 304. The
path of the GCIB 128 through the pressure chamber 304 has a path length d_1, along a path
D_1. Baffle 302 may have one or multiple openings 310 into the processing chamber 108.

The pressure chamber aperture **308** and any additional openings **310** into the processing

chamber **108** have a total combined gas conductance, C_P. The ionizing/acceleration chamber

aperture **306** has a gas conductance C_A. A pressurized gas **314** is stored in gas storage

cylinder **312**. Pressurized gas **314** is preferably an inert gas, preferably argon. A gas metering

5   valve **316** is preferably a mass-flow-control type metering valve and controls flow of

pressurized gas **314** through gas feed tube **318** and diffuser **320** into the pressure   chamber

304. Introducing gas **314** into the pressure chamber **304**, increases the pressure in pressure

chamber **304** relative to the base pressures in the ionizing/acceleration chamber **1 06** and the

processing chamber **108**.

10   Let:

    Q_{IN} represent the mass flow of gas into the pressure chamber **304** through the

    diffuser **320**,

    Q_A represents mass flow between the pressure chamber **304** and the

    ionizing/acceleration chamber **106** through the ionizing/acceleration chamber

15   aperture **306**,

    Q_P represents mass flow between the pressure chamber **304** and the processing

    chamber **108** through the processing chamber aperture **308** and the openings **310**,

    P_C represents the vacuum pressure in the pressure chamber **304**,

    P_P represents the vacuum pressure in the processing chamber **108**, which can be

20   measured using a conventional vacuum gauge (not shown in **Figure 2**), and

    P_A represents the vacuum pressure in the ionizing/acceleration chamber **106**,

    which can be measured using a conventional vacuum gauge (not shown in **Figure**

    2).

Then:

25   $Q_{IN} = Q_A + Q_P$ (conservation of mass)   Eqn. 3

$Q_{IN} = (P_C - P_A)C_A + (P_C - P_P)C_P$ Eqn. 4

$$P_C = \frac{Q_{IN} + P_A C_A + P_P C_P}{C_A + C_P}$$ Eqn. 5

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and for the case (preferred operating condition):

$$P_C \gg P_P \quad \text{and} \quad P_C \gg P_A, \text{ then} \qquad\qquad \text{Eqns. 6}$$

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$$P_C \cong Q_{IN} / (C_A + C_P) \qquad\qquad\qquad \text{Eqn. 7}$$

Since the conductances C_A and C_P can be calculated or experimentally determined, and the Q_{IN}

is controlled by gas metering valve **316**, preferably a mass flow control valve, and since P_C

and P_A can be measured by using conventional vacuum pressure sensors, it follows that by

10   using Eqn. 5 (or if conditions in Eqns. 6 are met, using Eqn. 7), P_C is expressed in terms of

known quantities and can be readily controlled by adjusting the gas metering valve **316**.

Alternatively and optionally, a pressure sensor **322** can be included in the pressure chamber

304. When present, the pressure sensor **322** is connected by cable **324** to pressure sensor

controller and readout **326**. Pressure controller and readout **326** directly reads out the

15   pressure in pressure chamber **304**.

In operation, pressure chamber **304** is operated at a pressure, P_C, greater than P_A and greater

than P_P. As GCIB **128** passes through pressure chamber **304** with elevated pressure,

characteristics of the GCIB are modified in a way that improves its suitability for certain

GCIB processing applications, as will be described hereinafter. The degree of modification of

20   the GCIB characteristics is related to the pressure, P_C, and to the GCIB path length, d_1, in the

pressure chamber **304**. More specifically, when P_C is approximately constant along the

GCIB path, D_1, the degree of modification of the GCIB characteristics is related to the

product of the pressure P_C and the path length d_1, ($P_C \cdot d_1$). When the pressure P_C in the

pressure chamber has some spatial variation along the path, D_1, then the degree of

25   modification of the GCIB characteristics is related to the integral from 0 to d_1, of ($P_C(x) \cdot dx$)

taken along the path D_1 (the pressure-distance integral (PDI)). The pressure – path length

product and/or the PDI can both be conveniently expressed in units of torr $\cdot$ cm.

Figure 3 shows a schematic of a GCIB processing apparatus **350** according to a second

embodiment of the present invention. A pressurized gas **314** is stored in gas storage cylinder

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312. Pressurized gas **314** is preferably an inert gas, preferably argon. A mass-flow-control

valve **352** controls flow of pressurized gas **314** through gas feed tube **318** and diffuser **320**

into the pressure chamber **304**. A general purpose controller **358**, which may be

programmable and microprocessor based, and which may be a controller which is also used

5   for control of all or a substantial portion of the GCIB processing apparatus **350**, receives

pressure measurement signals for the pressure in pressure chamber **304** from the pressure

sensor **322** via cable **324** , pressure sensor controller and readout **326**, and cable **3 60**.   The

controller **358** also controls the mass-flow-control valve **352** via cable **360**, mass-flow-control

valve controller **356**, and cable **354** to set and regulate the flow of gas **314** into the pressure

10   chamber **304**. According to whether the pressure measurement signals from pressure sensor

322 are used or not used, controller **358** has capability to control the pressure P_C in pressure

chamber **304** by either open loop or by closed loop control algorithms. Controller **358** may

also receive signals from other sensors and send control signals to other systems as part of a

general control of the GCIB processing apparatus **350** via cable **360** – these other connections

15   are symbolized by the identifier **362**.

Figure 4 shows a schematic of a GCIB processing apparatus **400** according to a third

embodiment of the present invention. Ionizing/acceleration chamber **106** and proc essing

chamber **108** communicate with each other and have substantially the same pressure, P_{P2}. A

pressure cell **402** has a pressure cell interior **408** that can be pressurized to a pressure P_{C2} that

20   is typically a higher pressure than P_{P2}. The pressure cell **402** has a pressure cell entrance

aperture **404** and a pressure cell exit aperture **406**. GCIB **128** enters the pressure cell **402**

through pressure cell entrance aperture **404** and exits the pressure cell **402** through pressure

cell exit aperture **406**. The path D_2 of the GCIB **128** through the pressure cell **402** has a path

length d_2, along the GCIB path D_2. The pressure cell entrance aperture **404** and the pressure

25   cell exit aperture **406** have a combined total gas conductance, C_{P2}. A pressurized gas **314** is

stored in gas storage cylinder **312**. Pressurized gas **314** is preferably an inert gas, preferably

argon. A mass-flow-control valve **352** controls flow of pressurized gas **314** through gas feed

tube **318** and diffuser **410** into the pressure cell **402**. The general purpose controller **358**, in

this embodiment, which may also be programmable and microprocessor based, and which

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may be a controller which is also used for control of all or a substantial portion of the GCIB processing apparatus **400**, receives pressure measurement signals for the pressure P_{P2} from the pressure sensor **412** via cable **324**, pressure sensor controller and readout **326**, and cable **360**. Controller **358** also controls the mass-flow-control valve **352** via cable **360**, mass-flow-

5 control valve controller **356**, and cable **354** to set and regulate the flow of gas **314** into the pressure chamber **304**. Depending upon whether the pressure measurement signals from pressure sensor **412** are used or not used, controller **358** has capability to control the pressure P_{C2} in pressure cell **402** by either open loop or by closed loop control algorithms. It is pointed out that the invention can be practiced by application of Eqn. 12, and thus the ability

10 to measure pressure P_{P2} is not essential to practice of the invention. Controller **358** may also receive signals from other sensors and send control signals to other systems as part of a general control of the GCIB processing apparatus **350** via cable **360** – these other connections are symbolized by the identifier **362**.

Let:

15   Q_{IN2} represent the mass flow of gas into the pressure cell **402** through the diffuser **410**,

        Q_{P2} represents mass flow between the pressure cell **402** and the processing chamber **108** and the ionizing/acceleration chamber **106** through the pressure cell entrance aperture **404** and the pressure cell exit aperture **406**,

20   P_{C2} represents the vacuum pressure in the pressure cell **402**,

        P_{P2} represents the vacuum pressure in the processing chamber **108** and in the ionizing/acceleration chamber **106**, which can be measured using pressure sensor **412**.

Then

25         $Q_{IN2} = Q_{P2}$ (conservation of mass)   Eqn. 8

        $Q_{IN2} = (P_{C2} - P_{P2})C_{P2}$ Eqn. 9

        $P_{C2} = (Q_{IN2} / C_{P2}) + P_{P2}$ Eqn. 10

and for the case (preferred operating condition):

$$P_{C2} \gg P_{P2}, \text{ then} \qquad \text{Eqn. 11}$$

$$P_{C2} \cong Q_{IN2} / C_{P2} \qquad \text{Eqn. 12}$$

Since the conductance C_{P2} can be calculated or experimentally determined, and the Q_{IN2} is controlled by mass-flow-control valve **352**, and since P_{P2} can be measured by using pressure sensor **412**, it follows that by using Eqn. 10 (or if the conditions in Eqn. 11 is met, using Eqn. 12), P_{C2} is expressed in terms of known quantities and can be readily controlled by adjusting the mass-flow-control valve **352**.

In operation, pressure cell **402** is operated at a pressure greater than P_{P2}. As GCIB **128** passes through pressure cell **402** with elevated pressure, characteristics of the GCIB are modified in a way that improves its suitability for certain GCIB processing applications. The degree of modification of the GCIB characteristics is related to the pressure, P_{C2}, and to the GCIB path length, d_2, in the pressure cell **402**. More specifically, when P_{C2} is approximately constant along the GCIB path, D_2, the degree of modification of the GCIB characteristics is related to the product of the pressure P_{C2} and the path length d_2, ($P_{C2} \cdot d_2$). When the pressure P_{C2} in the pressure cell has some spatial variation along the path D_2, then the degree of modification of the GCIB characteristics is related to the integral from 0 to d_1, of ($P_{C2}(x) \cdot dx$) taken along the path D_2 (the pressure-distance integral (PDI)). The pressure – path length product and/or the PDI can both be conveniently expressed in units of torr $\cdot$ cm.

Figure 5 is a graph showing results from measurement of GCIB characteristics after passing through a pressure cell under several pressure cell conditions (cases A through G). The original GCIB was an argon gas-cluster ion beam accelerated through a 30 kV potential difference. The graph plots the distribution of gas-cluster ion frequency (ordinate, arbitrary units) versus gas-cluster ion energy per charge (abscissa, keV/q). Cases A through G are for pressure cell PDI values of from 1.0×10^{-4} torr-cm to 1.3×10^{-3} torr-cm. The case A, 1.0×10^{-4} torr-cm, is substantially equivalent to the case where there is no pressure cell and shows a gas-cluster ion energy distribution that is narrow and peaked at approximately 22 keV/q.

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With increasing PDI values, the distributions broaden and the peak of the energy distribution moves to lower values. These modified distributions generally cannot be duplicated by simply lowering the beam accelerating potential (without the use of the invention). The distributions resulting from larger PDI values provide superior GCIB smoothing performance,

5   but lower etching rates.

Figure 6 is a graph showing dependence of GCIB etching rate on PDI value. In the case illustrated, workpieces having an SiO_2 surface were processed by an argon GCIB accelerated by an acceleration potential of 30 kV and irradiated to a total dose of 3 x10^{15} gas-cluster ions/cm^2. It is seen that at low PDI values, etch rate drops slowly with increasing PDI

10   values, but at high PDI values etch rate drops more rapidly and approaches zero.

Figure 7 is a graph showing dependence of final (end of process) surface roughness on PDI value, as measured by atomic force microscope. In the case illustrated, workpieces having an SiO_2 surface were processed by an argon GCIB accelerated by an acceleration potential of 30 kV and irradiated to a total dose of 3x10^{15} gas-cluster ions/cm^2. It is seen that at low PDI

15   values, end-of-process roughness drops rapidly with increasing PDI value, but at high PDI values, end-of-process roughness reaches a low value that does not improve further.

Figures 6 and 7 show data for etching and smoothing of SiO_2. However similar results have been obtained for a variety of workpiece materials, including metals, oxides, ceramics, and semiconductors, and the behavior is similar. For PDI (or pressure – path length products)

20   greater than 5x10^{-4} torr-cm, significant smoothing (and/or freedom from roughening) is achieved with minor reduction of etching rate. The combination of high etch rate with similarly good smoothing and/or freedom from roughening is often not obtainable by conventional ways of adjusting the GCIB source or adjusting the acceleration potential. With increasing PDI values, superior smoothing results are obtained but at progressively lower

25   etching rates. At high PDI values, many materials are smoothed to levels not obtained by conventional ways of adjusting the GCIB source.

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.

It is claimed:

1.   An apparatus for generating a gas-cluster ion beam with a modified gas-cluster ion

energy distribution, comprising:

a reduced-pressure chamber having a reduced-pressure;

a gas-cluster ion beam source within the chamber, for generating an energetic

gas-cluster ion beam having a gas-cluster ion beam path; and

a pressure-controlled region within the reduced-pressure chamber having an

average pressure greater than the reduced-pressure;

wherein at least a portion of the gas-cluster ion beam path traverses the

pressure-controlled region so as to be modified by the greater pressure of the

pressure-controlled region.

2.   The apparatus of claim 1, wherein the gas-cluster ion beam source further comprises:

a pressurized gas source;

a nozzle for expanding pressurized gas from the pressurized gas source into

the reduced-pressure chamber to form gas-clusters;

an ionizer for ionizing the gas-clusters to form a gas-cluster ion beam; and

an accelerator for accelerating the gas-cluster ion beam to form the energetic

gas-cluster ion beam.

3.   The apparatus of claim 1, wherein the portion of the gas-cluster ion beam path that

traverses the pressure-controlled region has a pressure-distance integral along the path

within the pressure-controlled region that is greater than about 5×10^{-4} torr-cm.

4.   The apparatus of claim 1, further comprising a control system for controlling the

average pressure in the pressure-controlled region.

5.   The apparatus of claim 1, wherein the energetic gas-cluster ion beam comprises gas-

cluster ions, at least a fraction of which are multiply ionized.

6.   The apparatus of claim 4, wherein the pressure-controlled region comprises a region within a pressure chamber,

7.   The apparatus of claim 1, wherein:

the reduced-pressure chamber further comprises an ionizing/acceleration chamber including the gas-cluster ion beam source;

the pressure-controlled region comprises a pressure chamber; and

the pressure chamber has a higher pressure than the ionizing/acceleration chamber.

8.   The apparatus of claim 7, wherein:

the reduced-pressure chamber further comprises a processing chamber; and

the pressure chamber has a higher pressure than the processing chamber.

9.   The apparatus of claim 1, wherein the pressure-controlled region comprises a region within a pressure cell.

10.   The apparatus of claim 9, wherein the gas-cluster ion beam source further comprises:

an ionizer for ionizing said gas-clusters to form a gas-cluster ion beam; and

an accelerator for accelerating said gas-cluster ion beam to form an energetic gas-cluster ion beam.

11.   The apparatus of claim 9, further comprising a control system for controlling a pressure in the pressure cell.

12.   The apparatus of claim 9, wherein the energetic gas-cluster ion beam comprises gas-cluster ions, at least a fraction of which are multiply ionized.

13.   The apparatus of claim 9, wherein the pressure cell has a higher pressure than the
reduced-pressure chamber.

14.   A method of processing a workpiece with a gas-cluster ion beam, comprising the steps
of:

        generating a gas-cluster ion beam with a gas-cluster ion beam source within a
reduced-pressure chamber;

        accelerating via an accelerator the gas-cluster ion beam to form an energetic gas-
cluster ion beam having a beam path;

        holding a workpiece within the reduced-pressure chamber;

        providing an increased-pressure region between the accelerator and the
workpiece, wherein at least a portion of the beam path traverses the increased-
pressure region.

15.   The method of claim 14, wherein the generating step further comprises:

        providing a pressurized gas source;

        providing a nozzle

        flowing pressurized gas through said nozzle for expanding the gas from said
pressurized gas source into said reduced-pressure chamber to form gas-clusters;

        providing an ionizer; and

        ionizing said gas-clusters to form the gas-cluster ion beam.


16.   The method of claim 14, further comprising the steps of:

        providing a control system for controlling a pressure in the increased-pressure
region; and

        controlling a pressure in the increased-pressure region with the control system.

17. The method of claim 14, wherein the at least a portion of the beam path that traverses the increased-pressure region has a pressure-distance integral along the path within the increased-pressure region that is greater than about 5×10^{-4} torr-cm.

18. The method of claim 14, wherein the energetic gas-cluster ion beam comprises gas-cluster ions, at least a fraction of which are multiply ionized.

19. A method of modifying the gas-cluster ion energy distribution in an accelerated gas-cluster ion beam comprising the steps of:

generating a gas-cluster ion beam with a gas-cluster ion beam source within the reduced-pressure chamber;

accelerating with an accelerator within the reduced-pressure chamber the gas-cluster ion beam to form an energetic gas-cluster ion beam having a beam path and a gas-cluster ion energy distribution;

providing an increased-pressure region in the reduced-pressure chamber;

directing the energetic gas-cluster ion beam path so as to traverse the increased-pressure region with at least a portion of the gas-cluster ion beam path, producing a gas-cluster ion beam with a modified gas-cluster ion energy distribution.

20. The method of claim 19, wherein the at least a portion of the gas-cluster ion beam path that traverses the increased-pressure region has a pressure-distance integral along the path within the increased-pressure region that is greater than about 5×10^{-4} torr-cm.

21. The method of claim 19, further comprising the steps of :

providing a control system for controlling a pressure in the increased-pressure region; and

controlling a pressure in the increased-pressure region.

22.   The method of claim 21, wherein the controlling step controls a pressure within the increased-pressure region such that the pressure-distance integral along the path is greater than about 5×10^{-4} torr-cm.

5   23.   The method of claim 19, wherein the energetic gas-cluster ion beam comprises gas-cluster ions, at least a fraction of which are multiply ionized.
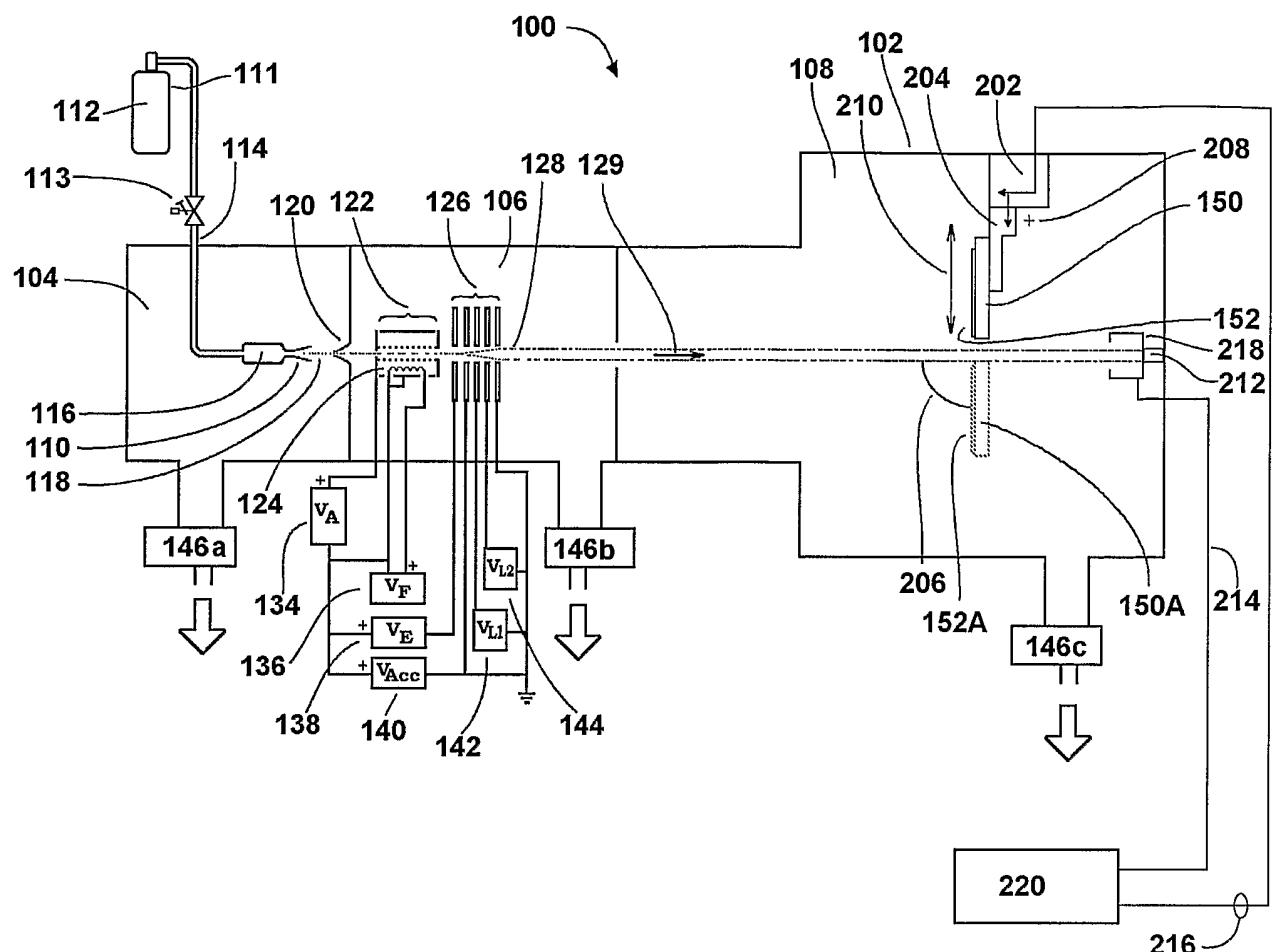
Figure 1   Prior Art.
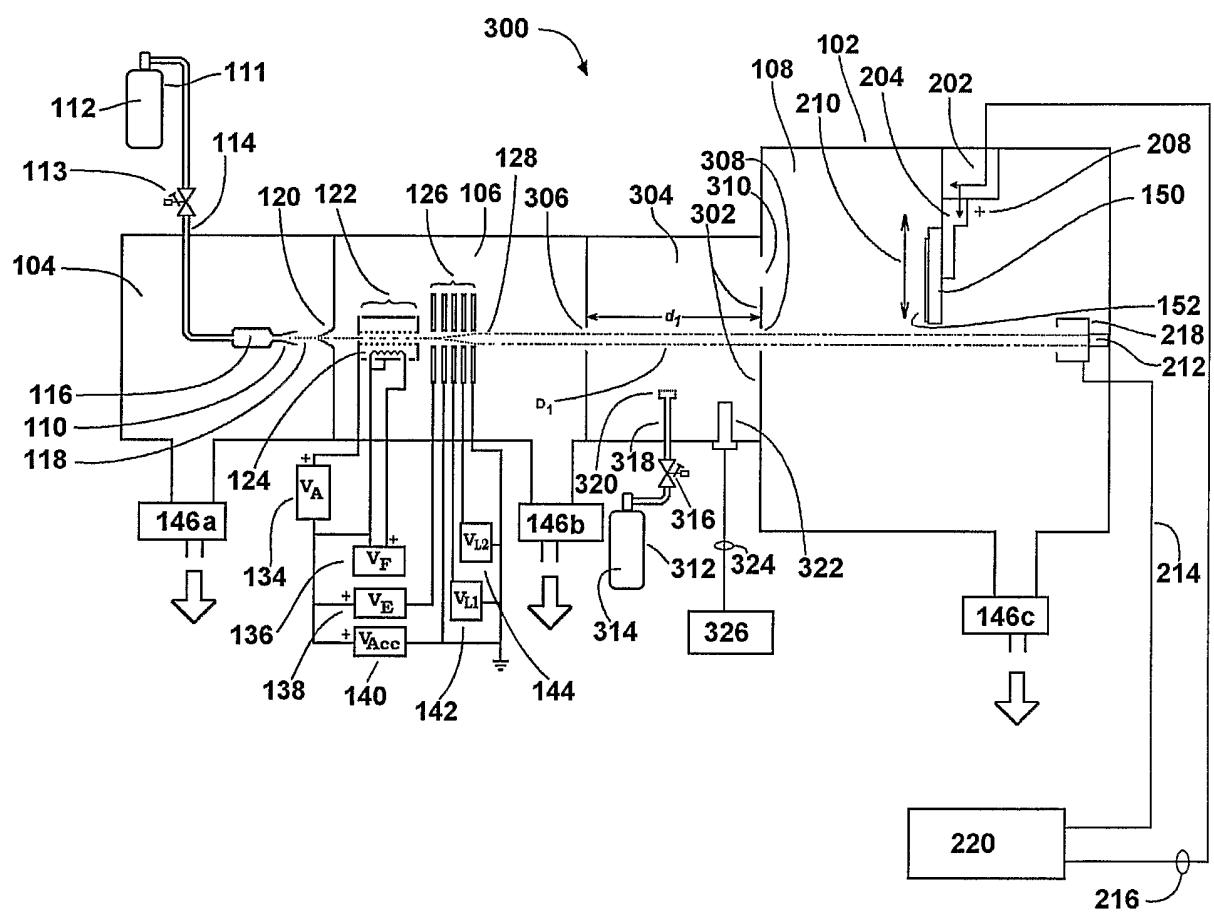
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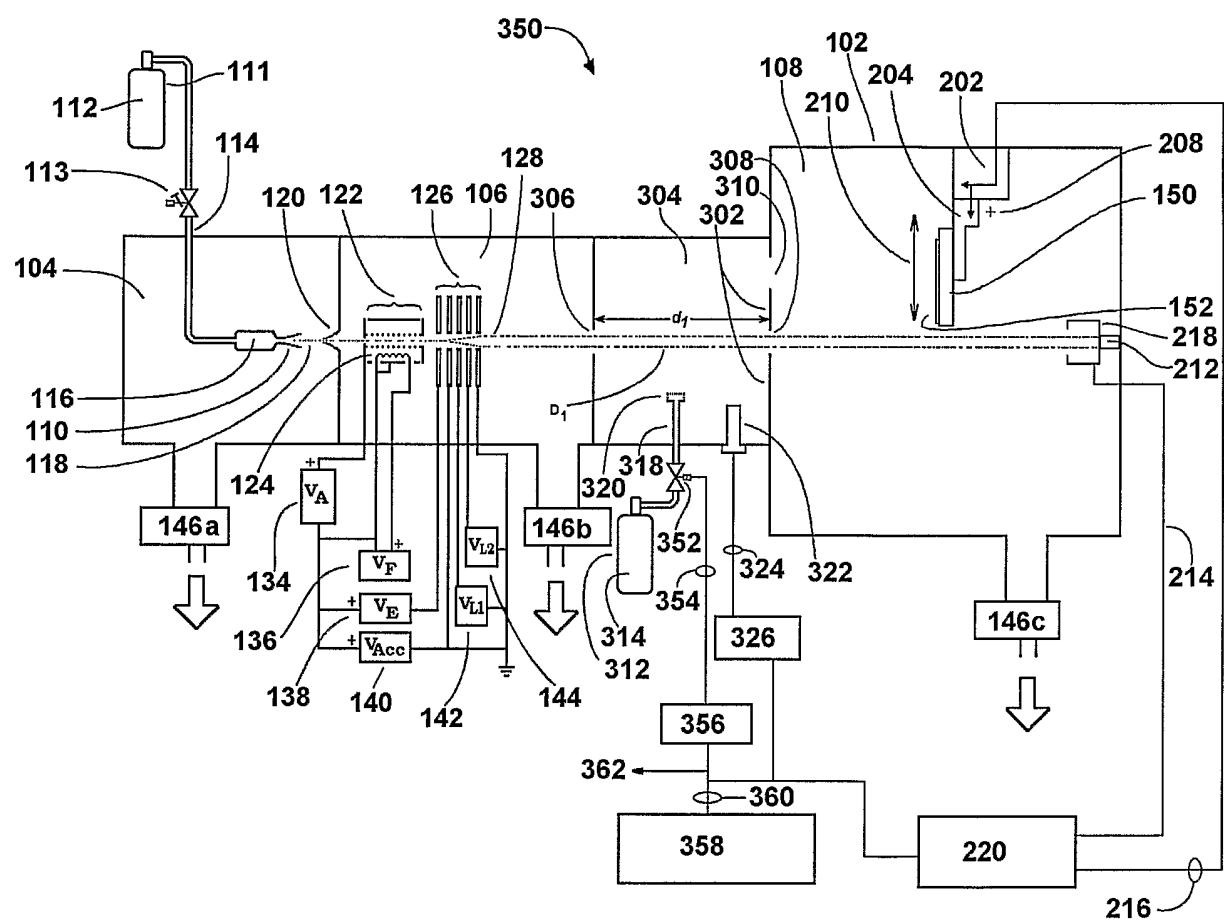
Figure 3

Figure 4

Figure 5

SiO₂ Etch vs. Pressure-Cell Conditions
(30 kV, 3E15/cm²)
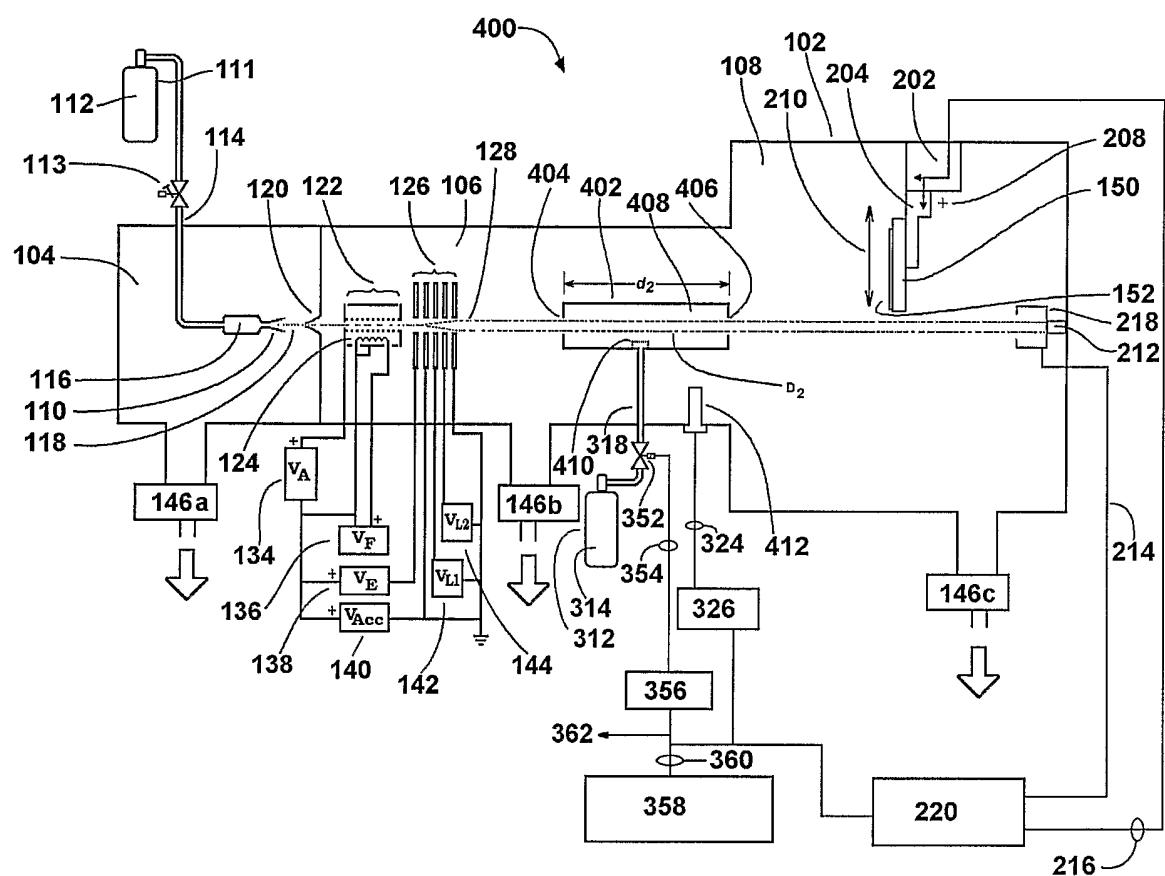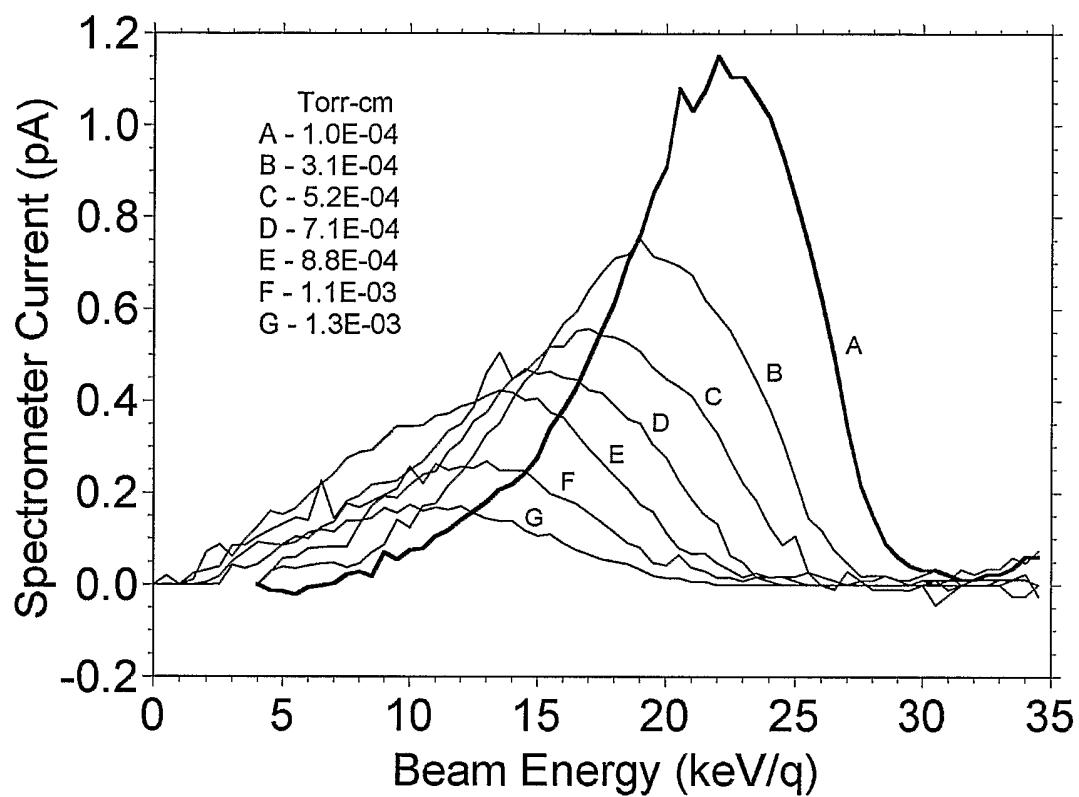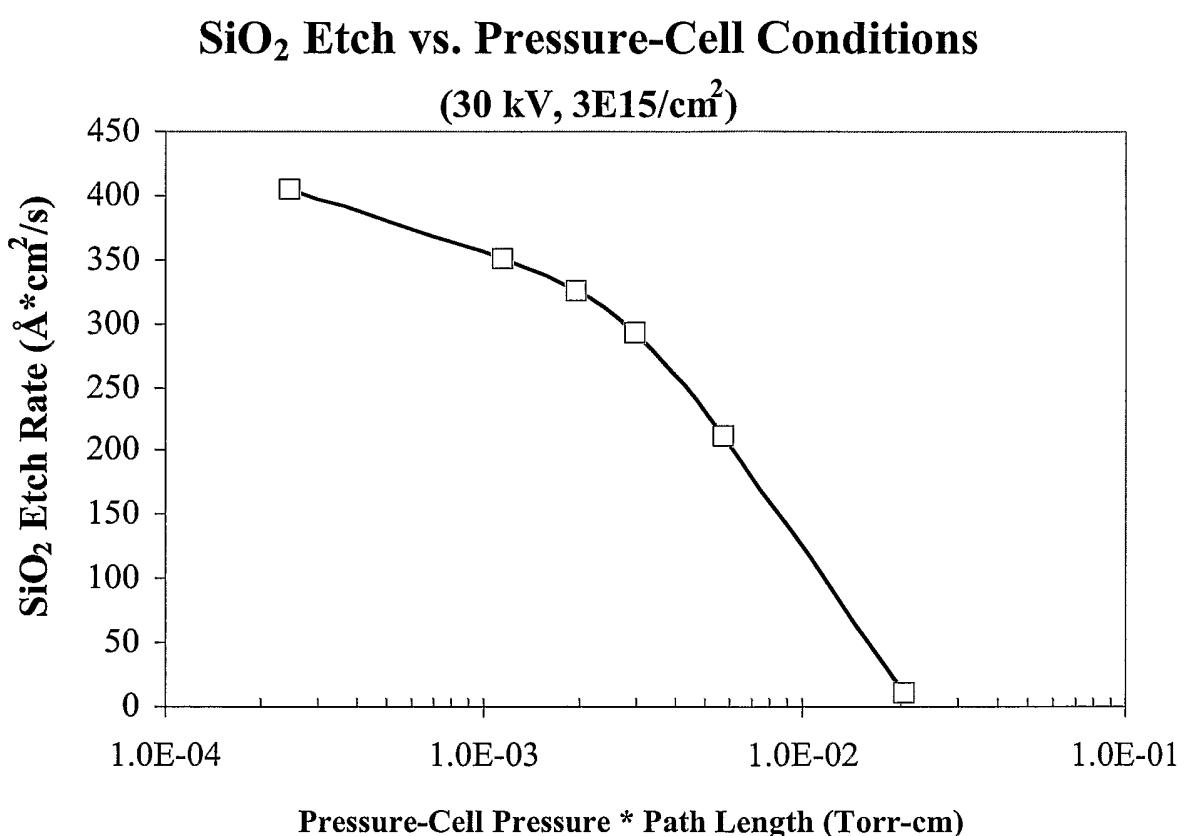
Figure 6

SiO$_2$ Roughness vs. Pressure-Cell Conditions
(30 kV, 3E15/cm2)

Figure 7