US009293301B2

(12) United States Patent
Biloiu et al.

(10) Patent No.: US 9,293,301 B2
(45) Date of Patent: Mar. 22, 2016

(54) **IN SITU CONTROL OF ION ANGULAR DISTRIBUTION IN A PROCESSING APPARATUS**

(71) Applicant: **Varian Semiconductor Equipment Associates, Inc.**, Gloucester, MA (US)

(72) Inventors: **Costel Biloiu**, Rockport, MA (US); **Nini Munoz**, Ithaca, NY (US); **Ludovic Godet**, Sunnyvale, CA (US); **Anthony Renau**, West Newbury, MA (US)

(73) Assignee: **Varian Semiconductor Equipment Associates, Inc.**, Gloucester, MA (US)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 53 days.

(21) Appl. No.: **14/139,679**

(22) Filed: **Dec. 23, 2013**

(65) **Prior Publication Data**

US 2015/0179409 A1 Jun. 25, 2015

(51) **Int. Cl.**
H01J 37/32 (2006.01)

(52) **U.S. Cl.**
CPC ***H01J 37/32357*** (2013.01); ***H01J 37/32422*** (2013.01); ***H01J 37/32568*** (2013.01)

(58) **Field of Classification Search**
USPC 250/492.21; 156/345.24, 345.51; 438/513, 710
See application file for complete search history.

(56) **References Cited**

U.S. PATENT DOCUMENTS

8,101,510	B2	1/2012	Godet et al.	
8,288,741	B1	10/2012	Miller et al.	
2002/0061598	A1	5/2002	Mutz et al.	
2007/0224709	A1 *	9/2007	Ogasawara	H01J 37/32642 438/5
2008/0132046	A1 *	6/2008	Walther	438/513
2009/0289193	A1 *	11/2009	Yamashita	250/396 R
2010/0255665	A1 *	10/2010	Godet	H01J 37/32623 438/513
2011/0079355	A1	4/2011	Brcka	
2013/0220549	A1	8/2013	Wilson	

OTHER PUBLICATIONS

International Search Report and Written Opinion Mailed Apr. 6, 2015 for PCT/US2014/069054 Filed Dec. 8, 2014.

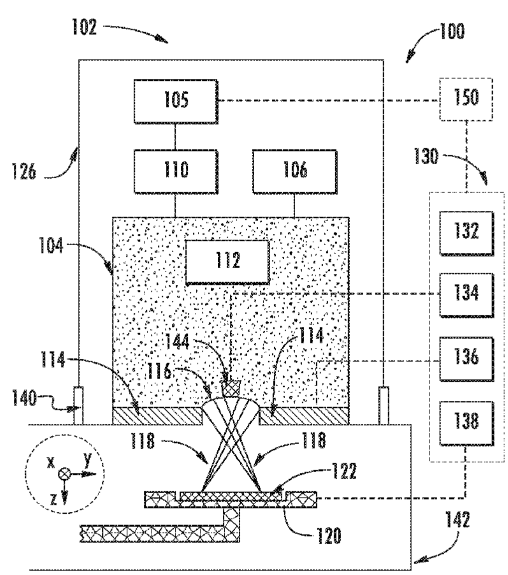
* cited by examiner

Primary Examiner — Phillip A Johnston
Assistant Examiner — Hsien Tsai

(57) **ABSTRACT**

A processing apparatus may include a plasma source coupled to a plasma chamber to generate a plasma in the plasma chamber, an extraction plate having an aperture disposed along a side of the plasma chamber; a deflection electrode disposed proximate the aperture and configured to define a pair of plasma menisci when the plasma is present in the plasma chamber; and a deflection electrode power supply to apply a bias voltage to the deflection electrode with respect to the plasma, wherein a first bias voltage applied to the deflection electrode is configured to generate a first angle of incidence for ions extracted through the aperture from the plasma, and a second bias voltage applied to the deflection electrode is configured to generate a second angle of incidence of ions extracted through the aperture from the plasma, the second angle of incidence being different from the first angle of incidence.

15 Claims, 10 Drawing Sheets



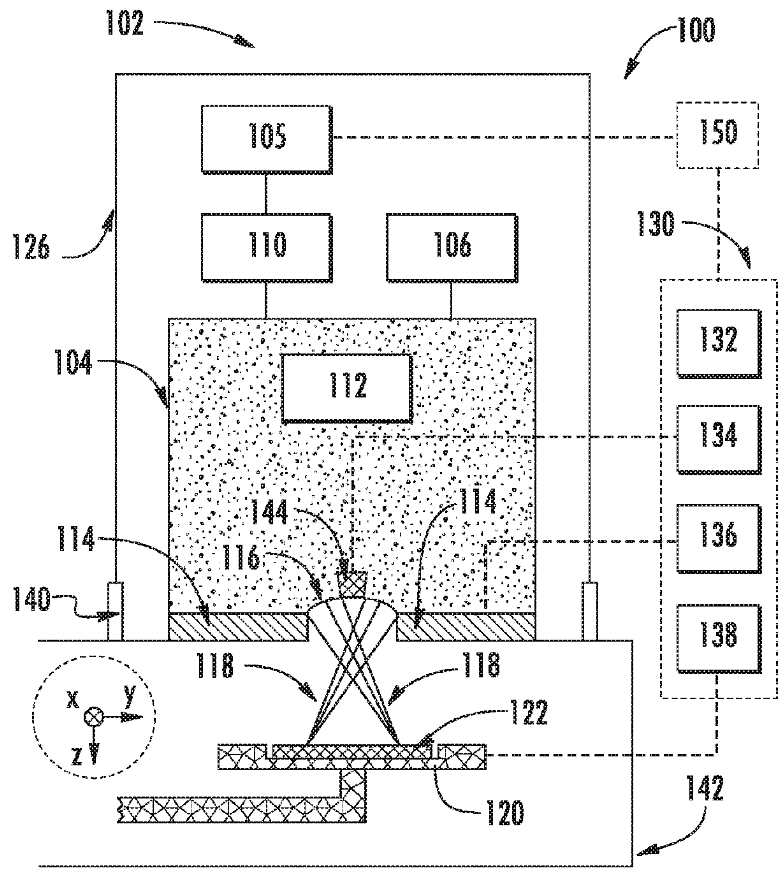

102
100
105
150
110
106
126
130
132
104
112
134
144
114
114
136
116
140
118
118
138
x
y
z
122
120
142

FIG. 1A

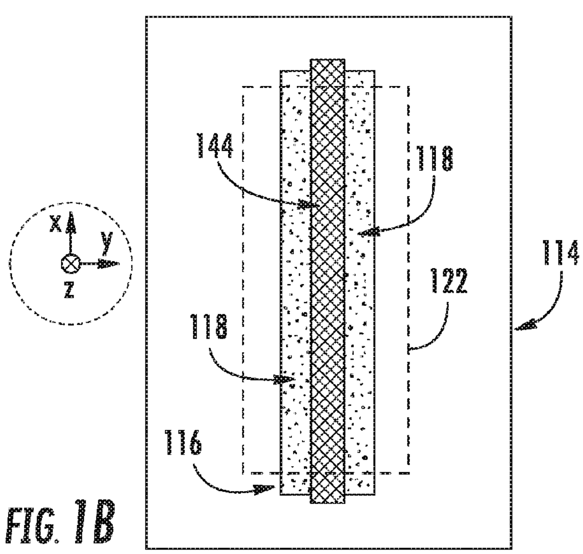

144
118
x
y
z
114
122
118
116

FIG. 1B

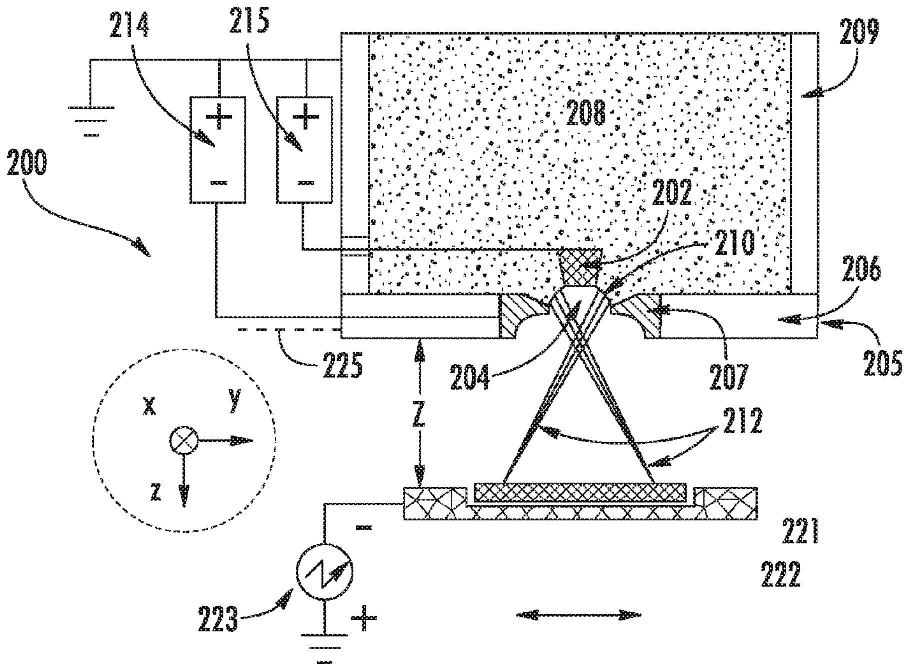

214
215
209
208
200
202
210
206
225
204
207
205
x
y
z
Z
212
221
222
223

FIG. 2A

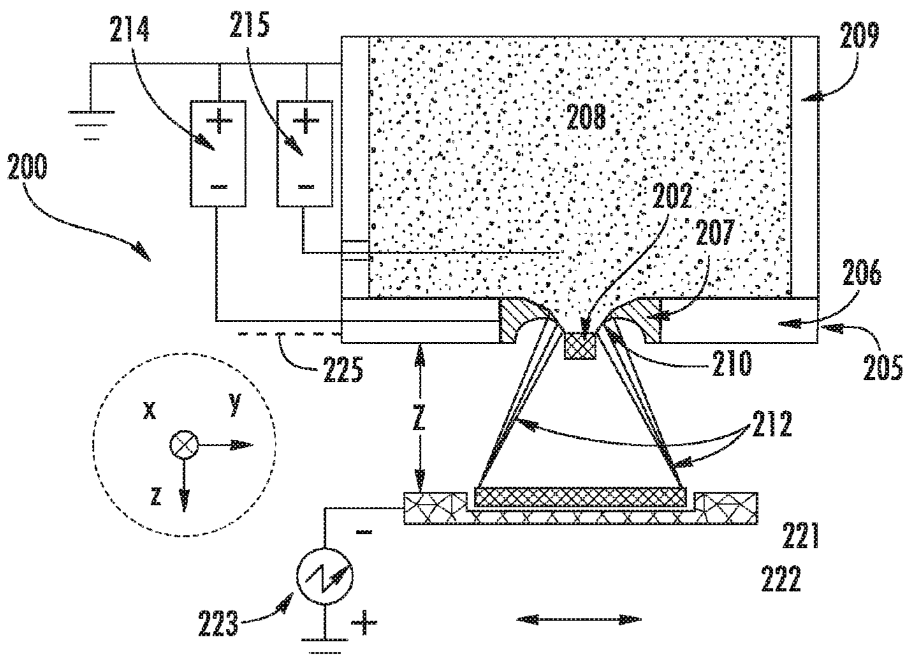

214
215
209
208
200
202
207
206
225
210
205
x
y
z
Z
212
221
222
223

FIG. 2B

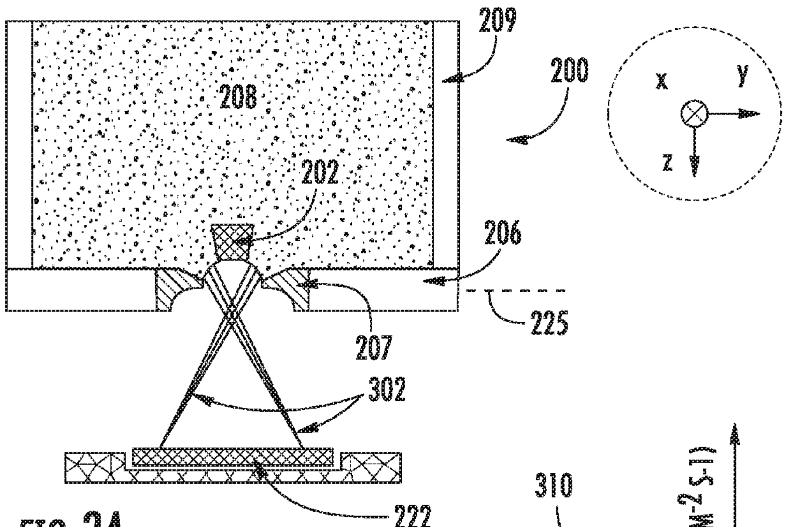


FIG. 3A

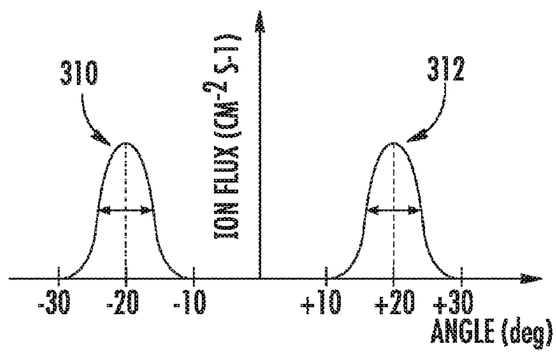


FIG. 3B

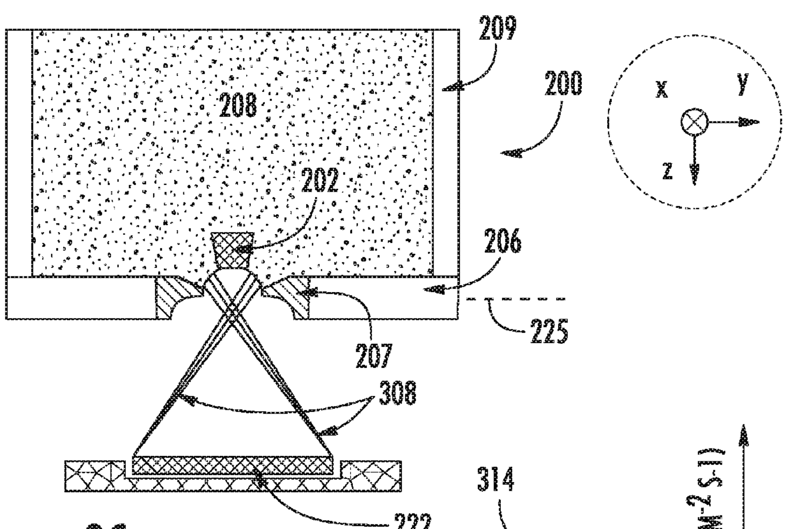


FIG. 3C

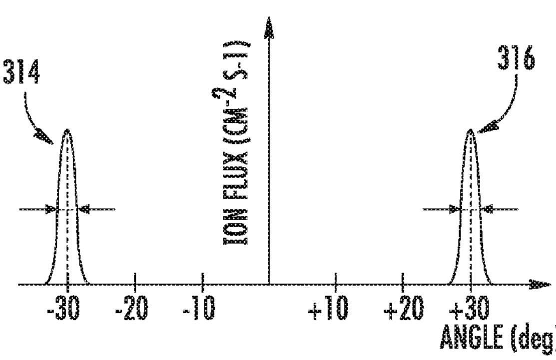


FIG. 3D

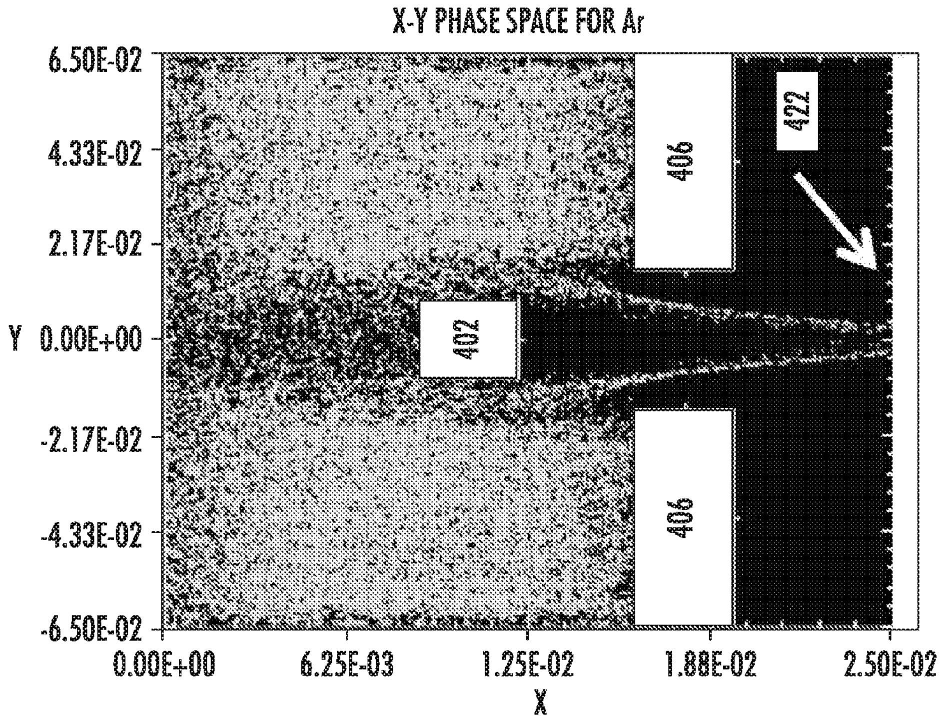

X-Y PHASE SPACE FOR Ar
6.50E-02
4.33E-02
2.17E-02
Y 0.00E+00
-2.17E-02
-4.33E-02
-6.50E-02
0.00E+00
6.25E-03
1.25E-02
1.88E-02
2.50E-02
X
406
422
402
406

FIG. 4B

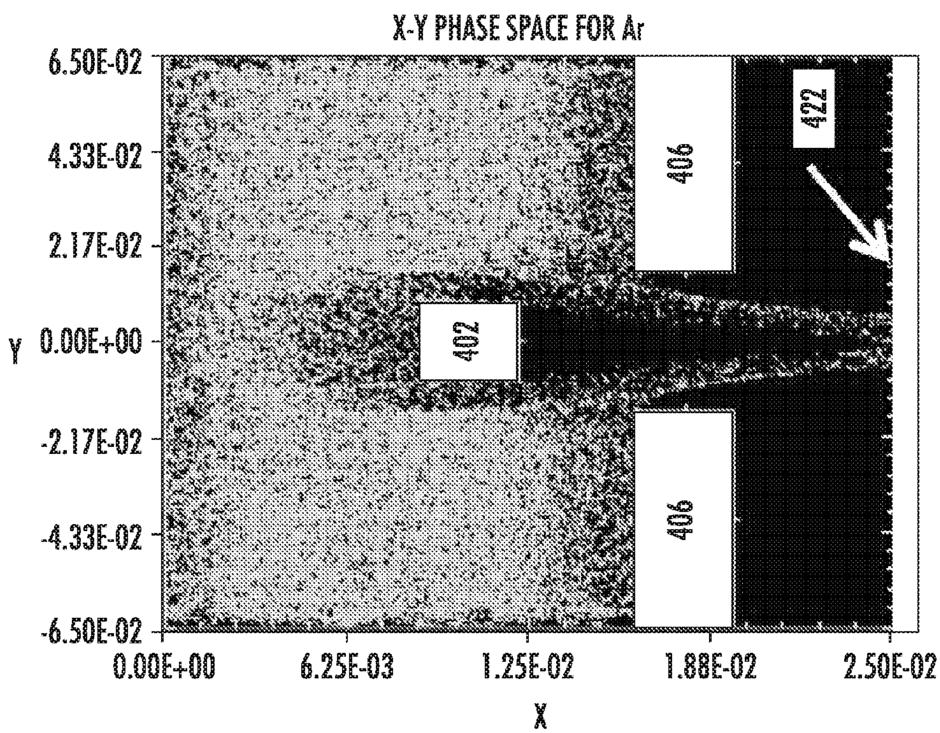

X-Y PHASE SPACE FOR Ar
6.50E-02
4.33E-02
2.17E-02
Y 0.00E+00
-2.17E-02
-4.33E-02
-6.50E-02
0.00E+00
6.25E-03
1.25E-02
1.88E-02
2.50E-02
X
406
422
402
406

FIG. 4A

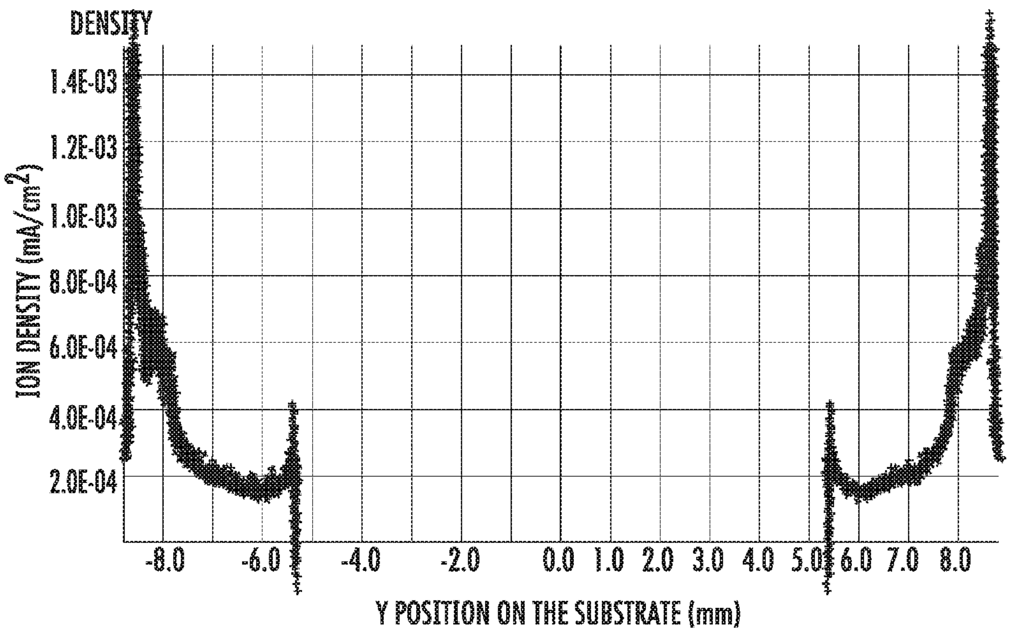

DENSITY
ION DENSITY (mA/cm2)
1.4E-03
1.2E-03
1.0E-03
8.0E-04
6.0E-04
4.0E-04
2.0E-04
-8.0
-6.0
-4.0
-2.0
0.0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0
Y POSITION ON THE SUBSTRATE (mm)

FIG. 5A

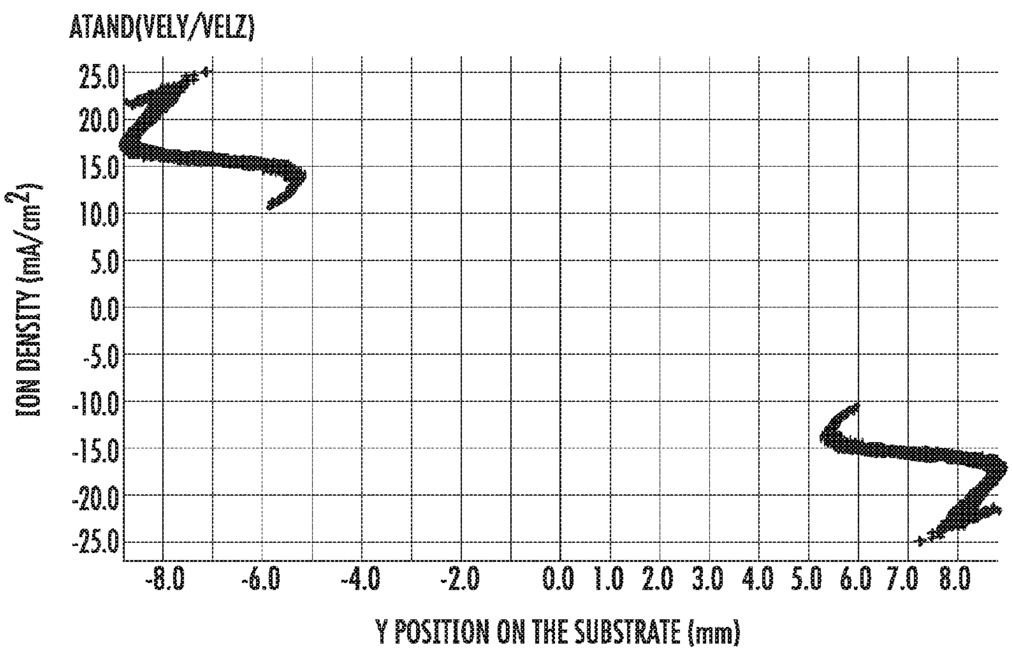

ATAND(VELY/VELZ)
ION DENSITY (mA/cm2)
25.0
20.0
15.0
10.0
5.0
0.0
-5.0
-10.0
-15.0
-20.0
-25.0
-8.0
-6.0
-4.0
-2.0
0.0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0
Y POSITION ON THE SUBSTRATE (mm)

FIG. 5B

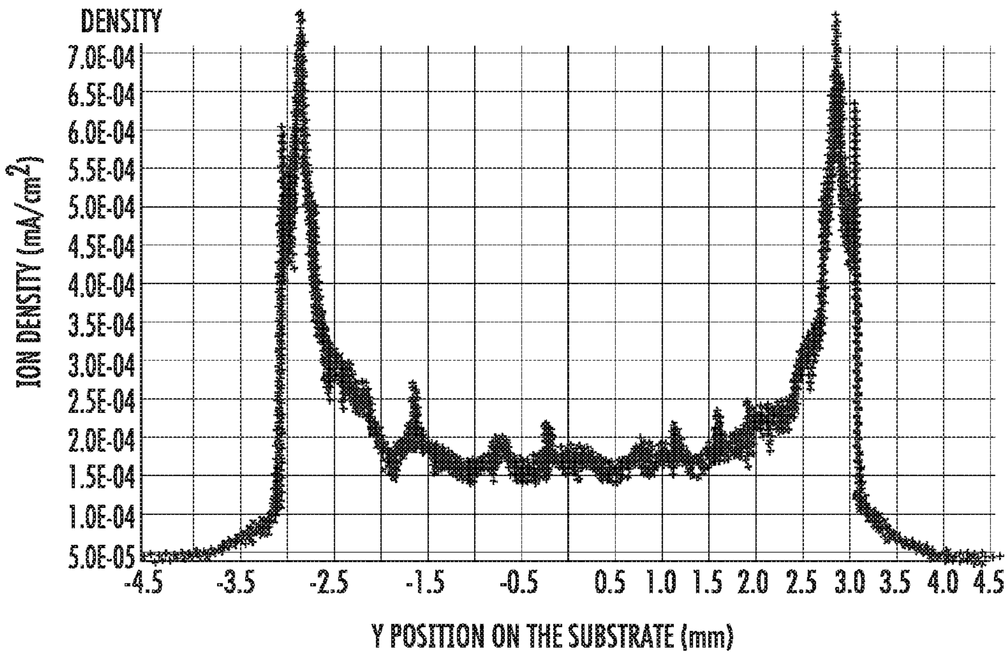

DENSITY
ION DENSITY (mA/cm2)
7.0E-04
6.5E-04
6.0E-04
5.5E-04
5.0E-04
4.5E-04
4.0E-04
3.5E-04
3.0E-04
2.5E-04
2.0E-04
1.5E-04
1.0E-04
5.0E-05
-4.5 -3.5 -2.5 -1.5 -0.5 0.5 1.0 1.5 2.0 2.5 3.0 3.5 4.0 4.5
Y POSITION ON THE SUBSTRATE (mm)

FIG. 5C

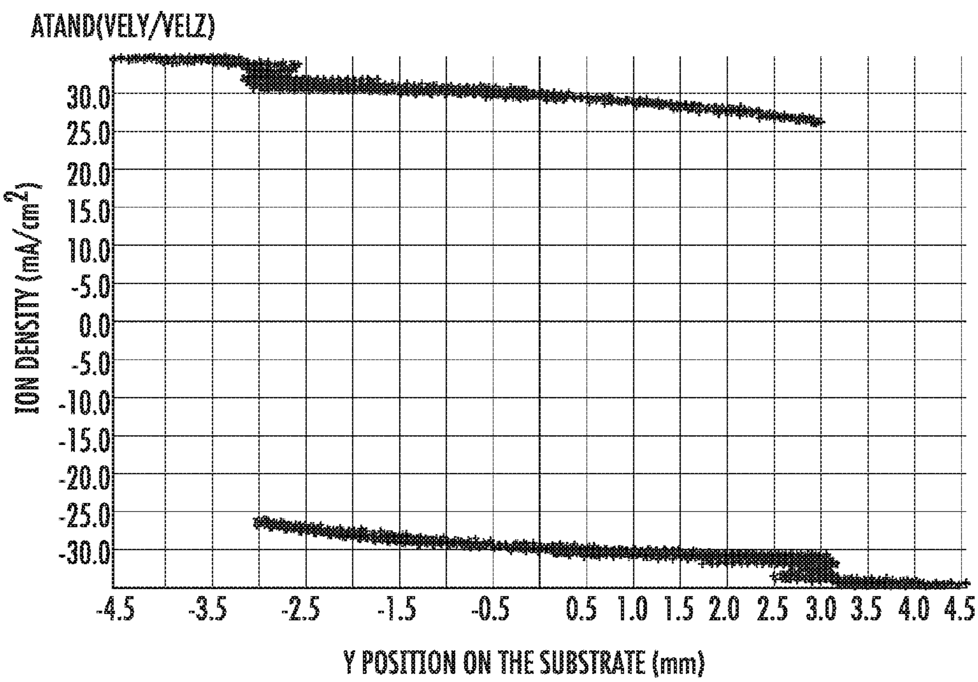

ATAND(VELY/VELZ)
ION DENSITY (mA/cm2)
30.0
25.0
20.0
15.0
10.0
-5.0
0.0
-5.0
-10.0
-15.0
-20.0
-25.0
-30.0
-4.5 -3.5 -2.5 -1.5 -0.5 0.5 1.0 1.5 2.0 2.5 3.0 3.5 4.0 4.5
Y POSITION ON THE SUBSTRATE (mm)

FIG. 5D

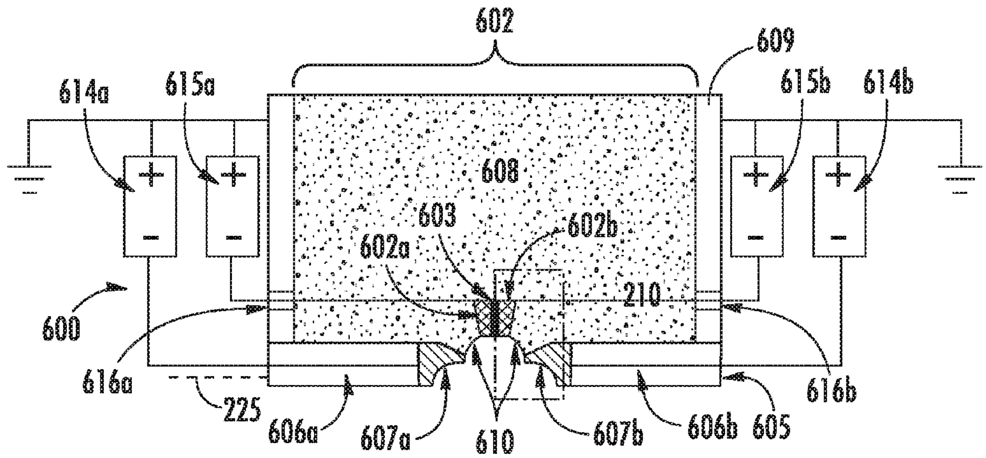


FIG. 6A

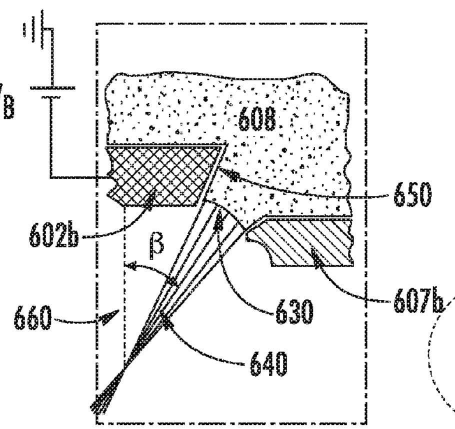


FIG. 6B

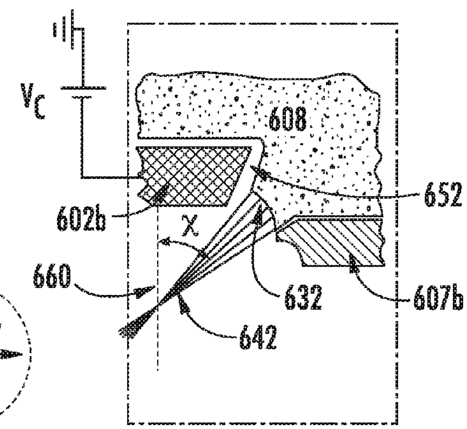


FIG. 6C

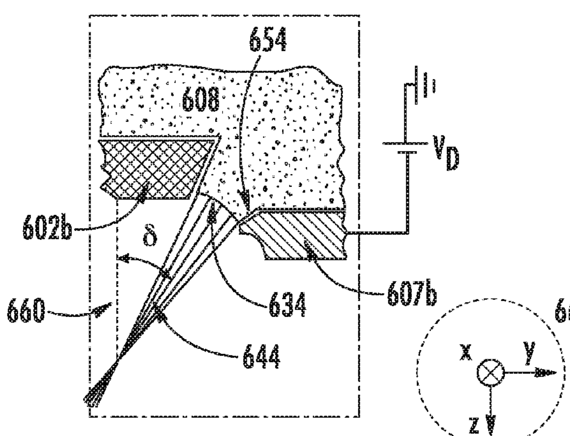


FIG. 6D

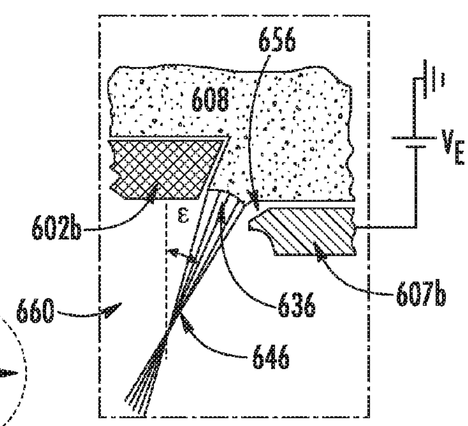


FIG. 6E

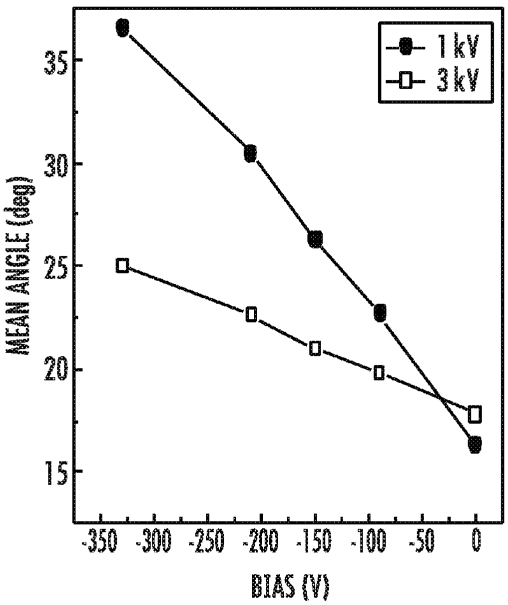


FIG. 7A

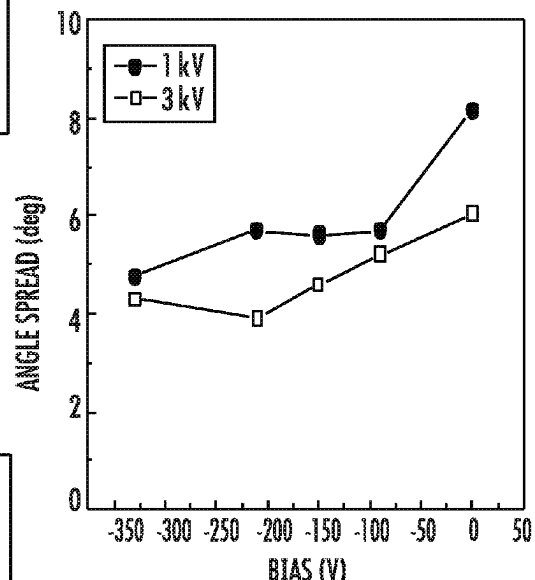


FIG. 7B

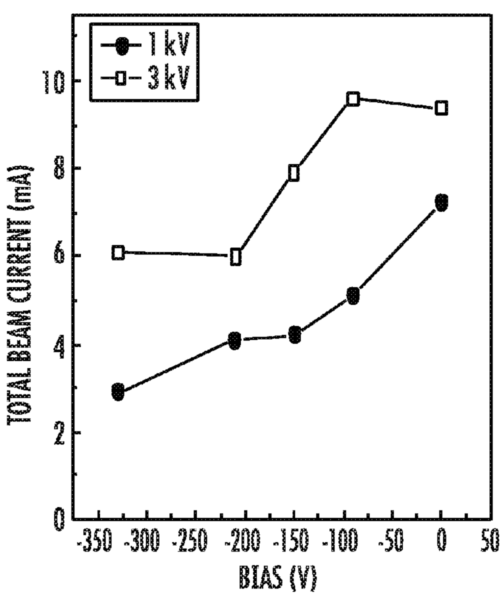


FIG. 7C

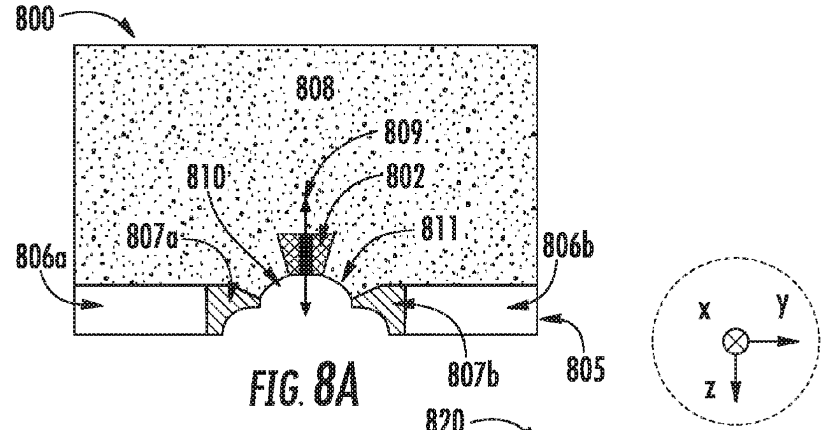


FIG. 8A

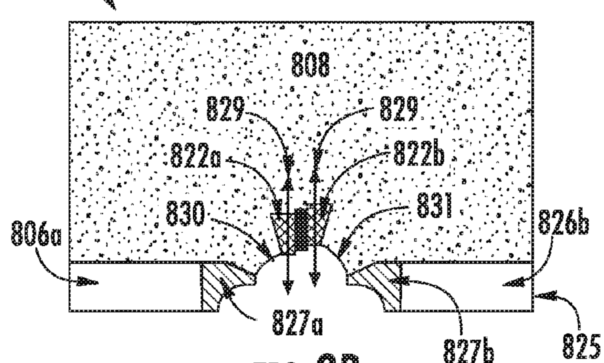


FIG. 8B

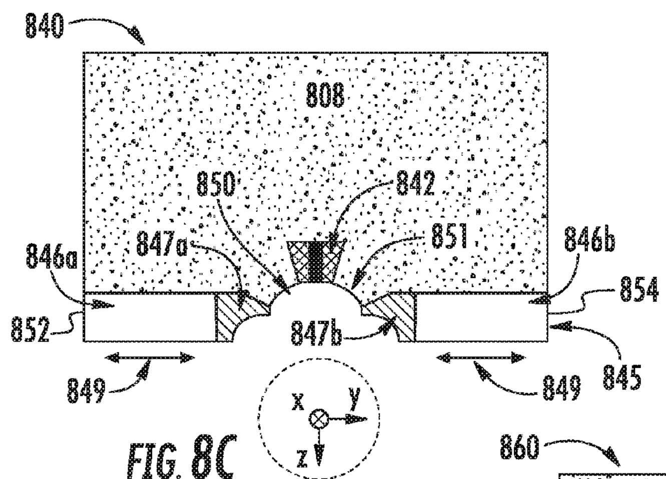


FIG. 8C

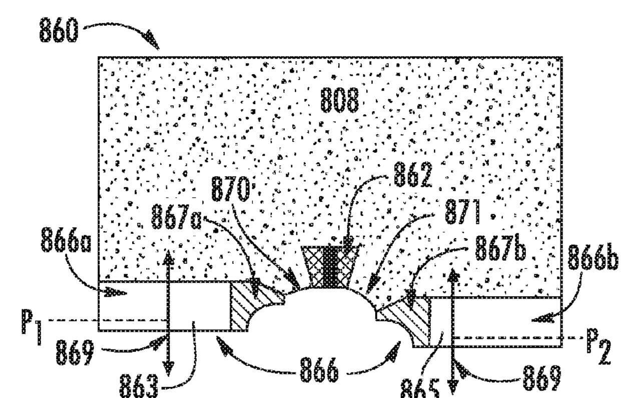


FIG. 8D

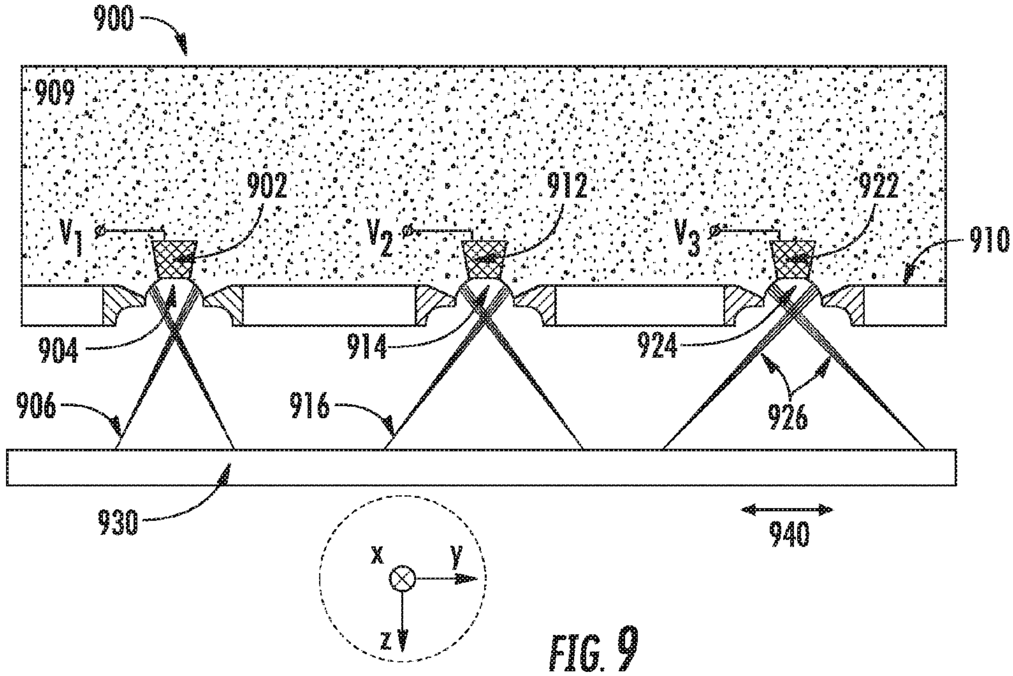

900
909
902
912
922
V1
V2
V3
910
904
914
924
906
916
926
930
940
x
y
z

FIG. 9

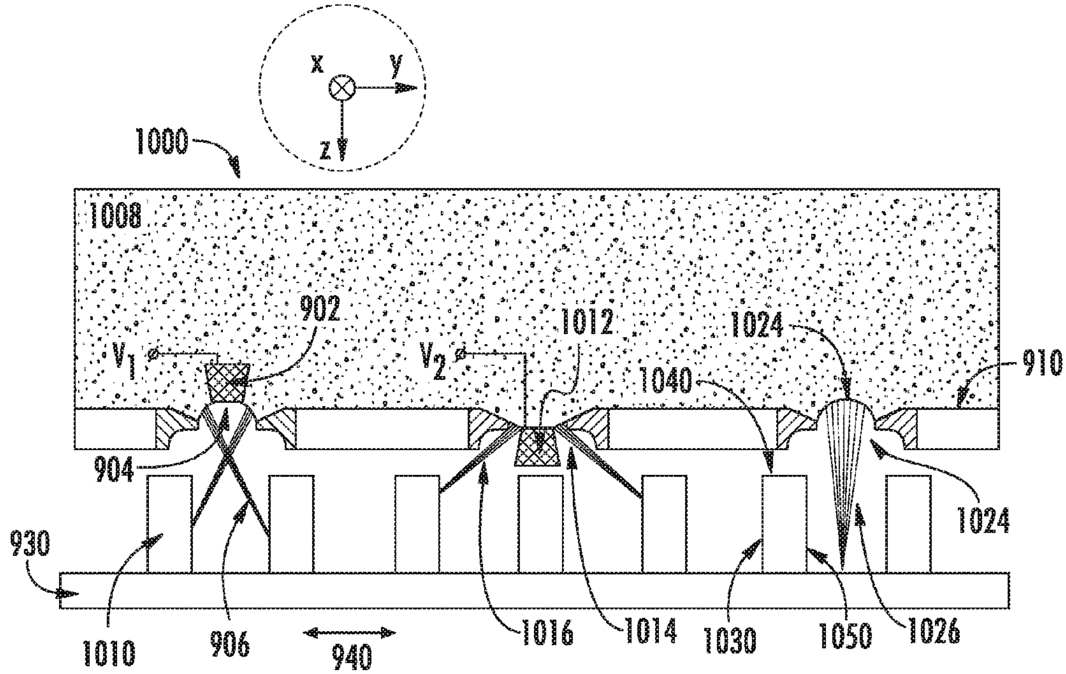

x
y
z
1000
1008
902
1012
1024
V1
V2
1040
910
904
1024
930
1010
906
940
1016
1014
1030
1050
1026

FIG. 10

IN SITU CONTROL OF ION ANGULAR DISTRIBUTION IN A PROCESSING APPARATUS

RELATED APPLICATIONS

1. Field

The present embodiments relate to a processing apparatus, and more particularly, to control of the angular distribution of the ions extracted from a plasma.

2. Background

Conventional apparatus used to treat substrates with ions include beamline ion implanters and plasma immersion ion implantation tools. Both are appropriate for implanting ions over a range of energies. In beamline ion implanters ions are extracted from a source, mass analyzed and then transported to the substrate surface. In plasma immersion ion implantation apparatus, a substrate is located in the same chamber the plasma is generated adjacent to the plasma. The substrate is set at negative potential with respect to the plasma and ions that cross the plasma sheath in front of the substrate impinge on the substrate at perpendicular incidence angle. Recently a new processing apparatus that allows control of extracted ion angular distribution (IAD) has been developed. In this apparatus ions are extracted from a plasma chamber but unlike the beamline where the substrate is located remotely from the ion source, the substrate is located proximate the plasma chamber. Ions are extracted through an aperture of special geometry located in an extraction plate that is placed proximate a plasma. Changing the geometry of the aperture allows changing of the ion angular distribution, i.e., the mean angle and angular spread of the ion distribution. This may be appropriate to treat substrates that present surface features whose sidewalls are to be exposed to ions, for the purposes of implantation, etching, or other processing. In order to treat such sidewalls, ions are extracted through the aperture of a shape and size to generate a desired ion angular distribution. However, it may be desirable to provide further control in a plasma system over ion angular distribution in order to process substrates more effectively. It is with respect to these and other considerations that the present improvements have been needed.

SUMMARY

In one embodiment, a processing apparatus includes a plasma source coupled to a plasma chamber to generate a plasma in the plasma chamber. The system may also include an extraction plate disposed along a side of the plasma chamber, the extraction plate having an aperture, a deflection electrode disposed proximate the aperture and configured to define a pair of plasma menisci when the plasma is present in the plasma chamber, and a deflection electrode power supply to apply a bias voltage to the deflection electrode with respect to the plasma. When a first bias voltage is applied by the deflection electrode power supply a first angle of incidence for ions extracted through the aperture from the plasma may be generated, and when a second bias voltage applied to the deflection electrode power supply a second angle of incidence of ions extracted through the aperture from the plasma may be generated, where the second angle of incidence is different from the first angle of incidence.

In a further embodiment, a method of controlling ion angular distribution in an ion beam provided to a substrate includes generating a plasma in a plasma chamber adjacent a process chamber that contains the substrate; providing an extraction plate having an aperture between the plasma chamber and process chamber; arranging a deflection electrode proximate the aperture; and varying a deflection electrode voltage applied to the deflection electrode from a first voltage to a second voltage, wherein the first voltage is configured to generate a first angle of incidence for ions extracted from the plasma, and second voltage is configured to generate a second angle of incidence of ions extracted through the aperture from the plasma, the second angle of incidence being different from the first angle of incidence.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1**A depicts a side view of a processing apparatus consistent with embodiments of this disclosure;

FIG. **1**B depicts a top view of an extraction system of the processing system of FIG. **1**A;

FIGS. **2**A and **2**B depict details of the extraction geometries of a processing system consistent with further embodiments;

FIGS. **3**A and **3**B depict one operation scenario for system of FIG. **2**A;

FIGS. **3**C and **3**D depict another operation scenario for the system of FIG. **2**A;

FIGS. **4**A and **4**B present results of simulation of ion trajectories in a processing system as a function of position of a deflection electrode with respect to an extraction plate;

FIGS. **5**A and **5**B present modeling results of the ion beam density distribution on the wafer and ion beam emissivity for a 0 Volt bias voltage;

FIGS. **5**C and **5**D present ion beam distribution and ion beam emissivity for −300 V bias voltage;

FIGS. **6**A, **6**B and **6**C depict qualitative illustrations of the effect of varying voltage V applied to a deflection electrode when the deflection electrode is placed inside the plasma source;

FIGS. **6**D and **6**E depict qualitative illustrations of the effect of varying voltage V applied to an extraction-plate when no voltage or a constant voltage is applied on a deflection electrode;

FIGS. **7**A-**7**C present experimental results on modification of ion angular distribution when a deflection electrode is biased;

FIGS. **8**A-**8**D present illustration of operation of various extraction components in processing apparatus according to different embodiments;

FIG. **9** depicts a portion of a processing system that includes an extraction plate provided with multiple apertures according to one embodiment; and

FIG. **10** depicts a portion of a processing system according to another embodiment that includes another extraction plate provided with multiple apertures.

DETAILED DESCRIPTION

The embodiments described herein provide apparatus and methods for controlling angular distribution of ions directed to a substrate. In particular, the present embodiments provide a novel extraction system to generate ion beams from a plasma and control their ion angular distribution (IAD). The term "ion angular distribution" refers to the mean angle of incidence of ions in an ion beam with respect to a reference direction such a perpendicular to a substrate, as well as to the width of distribution or range of angles of incidence centered around the mean angle, termed "angular spread" for short. In the embodiments disclosed herein the novel extraction system may include an extraction plate located adjacent a plasma and containing at least one aperture to extract ions from the plasma and accelerate ions toward a substrate based on electrical potential difference between the plasma and the substrate. The extraction system may also include a deflection electrode that is located proximate the aperture of the extraction plate and that serves to generate two ion beams. As detailed below, the angle of incidence of ion beams is controlled by adjusting voltages applied to the extraction system or adjusting positioning of the various components of the extraction system, or both.

FIG. **1**A depicts a processing apparatus **100** consistent with embodiments of this disclosure. Processing apparatus **100** includes a plasma source **102** to generate a plasma **112** in a plasma chamber **104**. Plasma source **102** may be an RF plasma source (inductively-coupled plasma (ICP) source, capacitively coupled plasma (CCP) source, helicon source, electron cyclotron resonance (ECR) source), indirectly heated cathode (IHC) source, glow discharge source, or other plasma sources known to those skilled in the art. In this particular embodiment, the plasma source **102** is an ICP source with an RF generator **105**, an RF matching network **110**. The transfer of the RF power from the RF generator to the gas atoms and/or molecules takes places through an antenna and a dielectric window (not shown). A gas manifold **106** is connected to the plasma source **102** through appropriate gas lines and gas inlets. The plasma source **102** or other components of the processing apparatus **100** also may be connected to a vacuum system (not shown), such as a turbo molecular pump backed by a rotary or membrane pump. The plasma source **102** is surrounded by an enclosure **126**, and an insulator **140** separates the enclosure **126** from a process chamber **142** that includes a substrate holder **120**. Plasma source **102** and substrate holder **120** may be at elevated electrical potential or may be electrically grounded whereas the process chamber **142** may be electrically grounded.

An extraction plate **114** may be arranged along a side of plasma chamber **104** as shown in FIG. **1**A. In the view of FIG. **1**A the extraction plate **114** is arranged at the bottom of the plasma chamber **104**. The extraction plate **114** in particular is disposed between the plasma chamber **104** and process chamber **142**. The extraction plate **114** may define a portion of a chamber wall of the plasma chamber or process chamber or both, in some instances. The extraction plate **114** includes an aperture **116** through which ions **118** may be extracted as ion beams and directed toward the substrate holder **120**.

The processing apparatus **100** further includes a plurality of voltage supplies used to drive the extraction optics and to control ion beam energy provided to the substrate **122**. These are illustrated collectively as an extraction voltage system **130**. In various embodiments, the extraction voltage system **130** may include a chamber power supply **132**, deflection electrode power supply **134**, extraction plate power supply **136**, and a substrate power supply **138**. In order to generate positive ion beams as represented by ions **118** having a desired energy at the substrate **122**, the substrate power supply **138** may bias the substrate holder **120** negatively with respect to ground, while the plasma chamber **104** is grounded. Alternatively, the plasma chamber **104** may be biased positively with respect to ground and the substrate holder **120** may be grounded or biased negatively with respect to ground. In some embodiments, the extraction plate **114** may be biased independently of the plasma chamber **104** using the extraction plate power supply **136** or may be floating. Similarly, the deflection electrode power supply **134** may be biased with respect to the chamber power supply **132**. The embodiments are not limited in this context.

Processing apparatus **100** also includes a control system **150** to control plasma density (by controlling the RF power and the gas pressure inside the plasma chamber) as well as ion energy and ion angular distribution (IAD) as detailed below. The control system **150** may include a combination of hardware and software components that direct operation of the RF generator **105**, mass flow controllers (not shown), and extraction voltage system **130**.

In various embodiments the substrate holder **120** may be coupled to a drive (not shown) that is configured to move the substrate holder **120** along a direction parallel to the Y axis of the Cartesian coordinate system shown. In further embodiments, the substrate holder **120** may be movable along a direction parallel to the X-axis, Z-axis, or both. This provides the processing apparatus **100** with two decrees of freedom, i.e., allows relative position of the substrate vs extraction aperture to be modified and allows the substrate **122** to be scanned with respect to the aperture **116** so that ions **118** may be provided over the entire surface of substrate **122** in some instances.

In various additional embodiments, and as detailed below, the extraction plate **114** may include separate portions that define the aperture **116**. The separate portions (not shown in FIG. **1**) may be movable with respect to one another along a direction parallel to the X-axis, Z-axis, or both

As further illustrated in FIG. **1**A, the processing apparatus **100** includes a deflection electrode **144** disposed proximate the aperture **116**. The deflection electrode **144** and extraction plate **114** may form part of an extraction system used to control ion beam extraction as discussed below. In various embodiments, the deflection electrode **144** may be an electrically conductive component that is coupled to the deflection electrode power supply **134** whose operation is detailed below. In brief, the deflection electrode **144** may function to adjust the optics of extraction of ions through the aperture **116**. As illustrated in FIG. **1**A, for example, when the deflection electrode **144** is located proximate the aperture **116**, ions **118** may be extracted through the aperture **116** as two different ion beamlets. In particular embodiments the extraction plate power supply **136** may be configured to apply an extraction plate voltage to the extraction plate **114** independently of a bias voltage applied to the deflection electrode **144** applied by the deflection electrode power supply **134**.

FIG. **1**B provides a plan view depiction of one embodiment of the extraction plate **114** and deflection electrode **144**. In this embodiment, the aperture **116** and deflection electrode **144** are elongated in the direction parallel to the X-axis, so as to extract ions **118** as ribbon beams. In various embodiments, ion beam width of the ions **118** along the X-axis may be greater than the dimension of the substrate **122** along the X-axis as illustrated. For example, for a substrate dimension along the X-axis of 30 cm, the width of an ion beam may be a few cm wider such as 33 cm, so that the substrate **122** is processed on its entire width in one pass. In the embodiments disclosed herein below, system parameters such as the RF power delivered to the antenna or voltage applied by components of processing apparatus **100** to different elements of the system, as well as positioning of the deflection electrode **144** and extraction plate **114** may be adjusted to tailor the extraction optics of ions and to provide ion beamlets to a substrate, such as the substrate **122**.

FIGS. **2**A and **2**B depict details of the extraction geometry of a processing apparatus **200** consistent with further embodiments. The processing apparatus **200** may include the same components as in processing apparatus **100** in some embodiments. In the embodiment depicted in FIG. **2**A a deflection electrode **202** is disposed proximate an aperture **204** defined by an extraction plate **205**. To prevent the extraction plate **205** from draining large ion currents from a plasma **208**, the extraction plate **205** is made of two parts: a large electrically non-conductive part **206** at the periphery of the extraction plate and a small electrically conductive part, inner portion **207**, which is disposed adjacent the aperture **204** and surrounding the aperture **204**. For the configuration shown in FIG. **2**A deflection electrode **202** is located inside the plasma source. In the configuration shown in FIG. **2**B, the deflection electrode **202** is located outside a plasma chamber **209** that contains the plasma **208**. Because of the natural geometric angle of this configuration, ion angular distributions characterized by large mean angles can be obtained. When the plasma **208** is generated in the plasma chamber **209**, two plasma menisci **210** form between the deflection electrode **202** and the edges of the inner portion **207** that define the aperture **204**. The inner portion **207** may be biased by an extraction plate power supply **214** and the deflection electrode **202** by a separate, deflection electrode bias power supply **215**. When a high voltage is applied between the substrate holder **221** which is electrically connected with the substrate **222** and plasma chamber **209** that houses plasma **208**, two ion beamlets **212** are directed at oblique incidence to the substrate **222**, that is, along trajectories that forms a non-zero angle with respect to the Z-axis as shown. The high voltage is provided by a high voltage power supply **223** and for the configurations shown in FIGS. **2**A and **2**B it has the negative polarity on the substrate holder so that positive ions are extracted from the plasma **208**. This oblique incidence may be useful for treating surfaces of features that may be aligned so their surfaces are not parallel to the X-Y plane. These kind of features are common for 3D semiconductor structures. In various embodiments, parameters such as the position of the deflection electrode **202** as well as voltages applied to different components of an extraction voltage system (see extraction voltage system **130** of FIG. **1**) may be adjusted to adjust the angle(s) of incidence and the angular spread of ion beam (s) directed to a substrate such as substrate **222**. In other embodiments, the high voltage difference between the plasma chamber **209** and substrate holder **221**/substrate **222**, is applied by the high voltage power supply **223** in which positive polarity is applied to the plasma chamber **209** and electrical ground on substrate holder **221**. In such configurations the extraction plate power supply **214** and the deflection electrode bias power supply **215** are referenced with respect to the high voltage power supply **223**, i.e., are floating at the plasma chamber potential.

FIGS. **3**A and **3**B depict one operation scenario for processing apparatus **200** in which a pair of ion beams **302** are extracted from the plasma **208** under a first set of conditions. For simplicity it may be assumed that ions within each of the ion beams **302** form a same mean angle with respect to perpendicular to the substrate **222** and form the same angular range of angles of incidence, where a mean angle is defined by the absolute value of the angle with respect to perpendicular unless otherwise noted. Thus an angle (+) θ with respect to perpendicular (the Z-axis direction) and an angle $-\theta$ with respect to perpendicular may be deemed to constitute the same mean angle. FIG. **3**B presents exemplary symmetrical ion angular distributions **310**, **312** which may represent the angular distributions of the pair of ion beams **302**. As illustrated, the mean angle of ion beams **302** is +/−20 degrees with respect to perpendicular (Z axis) to the substrate plane. The angular distribution depicted in FIG. **3**B is merely for exemplification purposes and is shown as a Gaussian shape. For this type of distribution the angular spread may be defined simply as the full width at half maximum (FWHM), which in this case is approximately 10 degrees. As will be shown later, in practice the ion angular distribution may have a much more complex shape, and depending of the extraction optics geometry, might be skewed toward lower or higher angles. For all distributions different than Gaussian distribution, the angular spread may be defined as half of the difference between the maximum and minimum angles of a particular beamlet.

FIGS. **3**C and **3**D depict another operation scenario for processing apparatus **200** in which a pair of ion beams **308** are extracted from a plasma **208** under a second set of conditions. For simplicity it may be assumed that ions within each of the ion beams **308** form a same mean angle with respect to perpendicular to the substrate **222** and form the same angular range of angles of incidence. FIG. **3**D presents exemplary symmetrical ion angular distributions **314**, **316** which may represent the angular distributions of the pair of ion beams **308**. As illustrated, the mean angle of ion beams **308** is +/−30 degrees with respect to perpendicular (Z axis) to the substrate plane. Similarly as for the distribution shown in FIG. **3**B, the angular spread of the distribution is the full width at half maximum (FWHM), which in this case is approximately 2 degrees.

Consistent with various embodiments, the variation in beam IAD characteristics (mean angle and angular spread) exhibited between the ion beams **302** and ion beams **308** may be generated by variation of any combination of changes in various parameters. The variation in beam geometry may be achievable without breaking vacuum of a processing apparatus. For this reason the present embodiments facilitate what is termed in-situ control of ion mean incidence angle, angular spread, in other words Ion Angular Distribution (IAD) of ions provided to a substrate. According to various embodiments in situ variation of ion angular distribution may be generated by changes in position of the deflection electrode **202**; variation in aperture size; changes in RF power delivered to the plasma **208**; changes of the gas pressure; or changes in voltages applied to components of the processing apparatus **200**, including voltage applied to the deflection electrode **202**, substrate holder **221**/substrate **222**, extraction plate **205**, or plasma chamber **209**. The embodiments are not limited in this context.

FIGS. **4**A and **4**B presents results of Object Oriented Particle In Cell (OOPIC) simulation of ion trajectories in a processing system as a function of position of a deflection electrode **402** with respect to extraction plate **406**. In the example shown, the sample ions are Ar^{+}. The extraction voltage between plasma and substrate **422** is assumed to be 3 kV and a bias applied to the deflection electrode **402** of −100 V. No bias is applied on the extraction plate **406**. In FIG. **4**A the deflection electrode **402** is positioned 3.5 mm above the extraction plate **406**, while in FIG. **4**B the deflection electrode is positioned 4.5 mm above the extraction plate **406**. As illustrated the ion trajectories become more pinched as the deflection electrode **402** is moved further from the extraction plate **406**. Also, the beamlets spread in the Oy direction becomes narrower as the deflection electrode is moved farther from the extraction plate.

FIGS. **5**A-D present results of modeling of the extracted ion beamlets using OPERA software. FIG. **5**A shows the ion density distribution on Oy direction at the location of the substrate surface for a 2 kV extraction voltage, 0 V bias voltage applied on the deflection electrode and unbiased extraction plate. There are two completely separated and symmetrical beamlets that span in the Oy direction from 5.2 mm to 9 mm and from −5.2 mm to −9 mm, respectively. The beamlets are strongly skewed toward higher y values with most of the beam hitting the substrate surface around ±8.8 mm. FIG. **5**B depicts the beamlets emissivity, i.e., the angular beam characteristics vs beam position in the Oy direction. As can be seen most of the ions hit the substrate surface with an angle between 13 and 17 degrees, which results in a mean angle of ~15 degrees and an angular spread of ~4 degrees. The orientation of the emissivity curve shows the beamlets are convergent. FIG. **5**C depicts ion density distribution on the substrate surface for identical conditions as for FIG. **5**A but deflection electrode bias voltage of −300 V. In this case two symmetrical beamlets also are obtained but they partially overlap. The beamlets are also skewed toward the extremities of the substrate but in this case the most of the ions hit the substrate between 2.5 and 3 mm and −2.5 and −3 mm, respectively. Beam emissivity depicted in FIG. **5**D shows that in this case the ions hit the substrate at an angle between 25 and 30 degrees. The beamlets are also slightly convergent but most of the ions hit the surface at 30 degrees.

In further embodiments the bias voltage applied to a deflection electrode or extraction plate may be adjusted to control ion beam trajectories i.e., ion angular distribution, for ions extracted through an aperture of a processing apparatus. In particular, a first bias voltage generated by a deflection electrode power supply may be configured to generate a first angle of incidence for ions extracted from plasma, while a second, different bias voltage generated by the deflection electrode power supply is configured to generate a second angle of incidence of ions extracted through the aperture that is different from the first angle of incidence. In some embodiments a deflection electrode may be a single electrode in which a single bias voltage is applied, while in other embodiments the deflection electrode may constitute multiple electrodes that are electrically isolated from one another and capable of receiving differing bias voltages.

FIG. **6**A depicts details of an extraction system that forms part of a processing apparatus **600** according to various embodiments. As illustrated the extraction system (not separately shown) includes an extraction plate **605** and a deflection electrode **602** that is separated in two deflection electrode parts, deflection electrode part **602***a* and deflection electrode part **602***b* by an electrical insulator **603**. Each part of the deflection electrode **602** can be biased independently by deflection electrode power supplies **615***a* and **615***b*. Connecting wires between the deflection electrode power supplies **615***a*,**615***b* and deflection electrode **602** may be passed inside a plasma chamber **609** through electrical feedthroughs **616***a* and **616***b*. They may also insulated from a plasma **608** with ceramic sleeves (not shown). The extraction plate **605**, which is located in the proximity of deflection electrode **602**, is composed of two dielectric parts, outer portions **606***a* and **606***b* and two electrically conductive parts, inner portions **607***a* and **607***b*. Each inner portion **607***a*, **607***b* may be biased independently by respective extraction plate power supplies **614***a* and **614***b*. When the plasma **608** is ignited a pair of plasma menisci **610** form between the deflection electrode part **602***a* and inner portion **607***a* on the one hand, and between deflection electrode part **602***b* and inner portion **607***b* on the other hand.

In brief, FIGS. **6**B and **6**C illustrate changes in the shape of a plasma meniscus is changed when deflection electrode bias voltage is varied while other parameters are held constant for a single deflection electrode-extraction plate inner portion pair. As illustrated, a meniscus **610** formed between inner portion **607***b* and deflection electrode part **602***b* may change substantially when bias voltage is varied. The change in shape may involve change in radius of curvature or may involve change in inclination of the meniscus with respect to a vertical plane crossing the deflection electrode **602**. This, in turn, leads to a change in the angle of ion trajectories for ions extracted from the plasma **608**. Similarly, FIGS. **6**D and **6**E illustrate changes in the shape of the plasma meniscus when extraction plate bias voltage is varied while other parameters are held constant. The change in shape may involve change in radius of curvature or may involve change in inclination of the meniscus with respect to a horizontal plane containing the tip of the extraction plate. This, in turn, leads to a change in the angle of ion trajectories for ions extracted from the plasma **608**.

In particular embodiments, the voltage applied to a deflection electrode such as deflection electrode **602** may be varied from 0 V to −500 V. Because of negative potential, a plasma sheath develops in front of the deflection electrode surface. The plasma sheath thickness s is given by:

$$S = \frac{\sqrt{2}}{3}\lambda_D\left(\frac{2\,V}{T_e}\right)^{3/4}. \tag{1}$$

where V is the absolute value of the negative biasing potential, T_e electron temperature and λ_D is the Debye length given by:

$$\lambda_D = \left(\frac{\varepsilon_0 k_B T_e}{e^2 n_e}\right)^{\frac{1}{2}} \tag{2}$$

where ϵ_0 is the permittivity of free space, k_B is Boltzmann constant, e is elementary charge, and n_e is electron density.

Returning to FIGS. **6**B-E, for clarity of the figures merely the rectangular area delimited by dotted lines in FIG. **6**A is shown. In FIG. **6**B the voltage V_B applied to the deflection electrode part **602***b* has a first value that is less than the voltage V_C applied to the deflection electrode in FIG. **6**C. In FIG. **6**B the plasma sheath **650** is relatively thin and the resulting plasma meniscus **630** relatively more horizontally (with reference to the horizontal X-Y plane) inclined as compared to its counterpart, plasma meniscus **632** formed in FIG. **6**C. This yields a mean angle β with respect to a perpendicular **660** to the plane Oxy, which is shown for ions of the ion beam **640** extracted from the plasma **608**. Turning to FIG. **6**C, the plasma sheath **652** is relatively thicker because the voltage V_C is more negative. The plasma **608** is accordingly pushed further inside the plasma chamber adjacent the deflection electrode part **602***b*. As a result the location and the shape of the plasma meniscus **632** is modified, resulting in a more vertically oriented plasma meniscus **632**. This, in turn leads to larger ion mean angle χ for ions of ion beam **642** as compared to mean angle β of FIG. **6**B.

In FIG. **6**D the voltage V_D applied to the inner portion **607***b* has a first value that is less than the voltage V_E applied to the extraction plate in FIG. **6**E. In FIG. **6**D the plasma sheath **654** is relatively thin and the resulting plasma meniscus **634** relatively more vertically (with reference to the horizontal X-Y plane) inclined as compared to its counterpart, plasma meniscus **636** formed in FIG. **6**E. This yields a mean angle δ with respect to a perpendicular **660** to the plane Oxy, which is shown for ions of the ion beam **644** extracted from the plasma **608**. Turning to FIG. **6**E, the plasma sheath **656** is relatively thicker because the voltage V_E is more negative. The plasma **608** is accordingly pushed further inside the plasma chamber **609** (see FIG. **6**A) adjacent the inner portion **607***b*. As a result the location and the shape of the plasma meniscus **636** is modified, resulting in a more horizontally oriented plasma meniscus **636**. This, in turn leads to a smaller ion mean angle ∈ for ions of ion beam **646** as compared to mean angle δ of FIG. **6**D.

It is to be noted that in some implementations the deflection electrode **602** may be composed of two symmetrical deflection electrode parts, deflection electrode part **602***a* and deflection electrode part **602***b*; similarly, the extraction plate **605** may have two symmetrical inner portions, inner portion **607***a* inner portion **607***b* as shown in FIG. **6**A. This may result in formation of symmetric menisci that form on opposite sides of the deflection electrode **602** as suggested in FIG. **6**A. Thus, in addition to ion beams **640**, **642**, **644**, and **646**, second ion beams (not shown) having a mean angle of $-\beta$, $-\chi$, $-\delta$, and $-\in$ with respect to perpendicular **660** may be generated in the scenario of FIGS. **6**B, **6**C, **6**D, and **6**E. In other embodiments, bias voltages driven by the bias power supplies **614***a* and **614***b* and **615***a* and **615***b* may be controlled independently. In this manner a first meniscus formed between deflection electrode part **602***a* and inner portion **607***a* may be different in shape and orientation from a second meniscus determined by the deflection electrode part **602***b* and inner portion **607***b*. In this case different ion angular distributions may be obtained for each beamlet generated from the first and second meniscus. In the case in which bias voltages on deflection electrode parts **602***a* and **602***b* are identical and bias voltages of the inner portion **607***a* and inner portion **607***b* of extraction plate **605** are identical, but not necessarily equal to the deflection electrode bias voltage, the processing apparatus **600** is configured to deliver two symmetrical beamlets characterized by mean angles θ and $-\theta$ and same angular spread $\Delta\theta$. To obtain different ion angular distributions, bias voltages can be configured in different ways: either merely deflection electrode parts **602***a* and **602***b* are biased (different or equal voltages), either merely inner portion **607***a* and inner portion **607***b* of the extraction plate **605** are biased (different or equal voltages), both deflection electrode part **602***a* and deflection electrode part **602***b* and inner portion **607***a* and inner portion **607***b* are biased, or any combination of extraction plate and deflection electrode bias is applied.

It is to be noted that in the present embodiments the cross-sectional shape of a deflection electrode (in the Y-Z plane) may be any convenient shape appropriate for providing control of plasma menisci, such as a rectangular, triangular, circular, elliptical, and so forth. In addition, deflection electrode may be located inside the plasma source or outside the plasma source.

FIG. **7**A-C depicts experimental results of measurements of mean angle, angle spread and ion beam current as a function of bias voltage applied to a deflection electrode arranged in conjunction with an extraction plate aperture as described above with respect to FIG. **6**A. Two particular conditions are shown: 1 keV and 3 keV ion energy. The bias voltage applied to the deflection electrode ranges between 0 and −330 V. No bias voltage is applied to the extraction plate. As is evident form FIG. **7**A, a linear increase in mean angle takes place as a function of increasingly negative bias voltage applied to the deflection electrode. Over this bias voltage range the mean beam angle changes from 15 degrees to 36 degrees for 1 keV beam ion beam energy, and from 18 degrees to 25 degrees for 3 keV ion beam energy, where the larger angle represents a greater deviation from perpendicular incidence (along the Z-axis). This change represents a change in the mean angle of 0.06 degrees per volt of bias voltage for 1 keV beam energy and 0.02 degrees per volt of applied bias voltage for the 3 keV beam energy, respectively. This difference in the slope of mean angle vs bias voltage appears due to different electrostatic configurations of the extraction optics: at 3 keV extraction voltage (i.e., beam energy) electric field lines protrude deeper into the plasma than at 1 keV extraction voltage; consequently it is harder for the bias voltage to shape the plasma meniscus at higher extraction voltage than at lower extraction voltage Thus, processing apparatus arranged according to the embodiments of FIGS. **6**A-**6**E present a convenient manner to tune ion beam incidence angle for ions directed to a substrate by varying bias applied to a deflection electrode over an easily accessible voltage range.

In addition to causing a change in the orientation of the plasma meniscus and thereby a change in beam angle as suggested by FIGS. **6**A-E, changes in voltage applied to a deflection electrode may change the curvature of the plasma meniscus. Such change may result in a different ion angle spread for ions extracted from the plasma. As shown in FIG. **7**B, ion angular distribution becomes tighter as the bias voltage is increased in absolute value: from 8 degrees at 0 bias voltage down to 4-5 degrees at −330 volts.

Changes of the ion angular distribution characteristics by changing the deflection electrode bias voltage are accompanied by changes in the extracted ion beam current. As shown in FIG. **7**C, as the bias voltage is increased in absolute value, the extracted ion beam current decreases monotonically, from 9 mA down to 6 mA in the case of 3 keV ion beam energy and from 6 mA down to 3 mA for the 1 keV ion beam energy, respectively. This effect is a result of two physical phenomena: a decrease in the meniscus area and a decrease of ion density in the vicinity of the deflection electrode.

In various additional embodiments, voltage applied to a deflection electrode or extraction plate may be adjusted in conjunction with in situ adjustments to extraction geometry, where the extraction geometry includes the relative position of deflection electrode and aperture, relative size of aperture, and relative position of different deflection electrode components, and aperture plate components, among other factors.

In particular embodiments, the deflection electrode and extraction plate are interoperative to adjust the angle of incidence of an extracted ion beam by movement of at least one extraction component with respect to another, such as movement of the deflection electrode or aperture plate. In some instances, the movement of the deflection electrode may involve movement of the first portion of the deflection electrode with respect to a second portion of the deflection electrode. Similarly, in other instances, the movement of the aperture plate may involve movement of a first portion of an aperture plate with respect to a second portion of the aperture plate. Any combination of such movements may alter the shape or size or both of a meniscus used to extract the ion beamlets and thereby alter the angle of incidence and the angular spread.

FIGS. **8**A-**8**D present illustration of operation of different extraction components in processing apparatus according to different embodiments. The extraction components include a deflection electrode and aperture plate in these illustrations. In FIG. **8**A, a portion of a processing apparatus **800** is illustrated showing an extraction plate **805** composed of electrically non-conductive parts **806***a* and **806***b* and electrically conductive parts, inner portions **807***a* and **807***b*. The extraction plate **805** is positioned adjacent a plasma **808**. A deflection electrode **802** is located adjacent the aperture (not separately shown) defined by the inner portions **807***a* and **807***b*. In this embodiment the deflection electrode **802** is movable along an axis **809** parallel to the Z-axis for the Cartesian coordinate system shown. This axis **809** lies perpendicular to the X-Y plane which defines a plane of the extraction plate **805**. Thus, the deflection electrode **802** may move away from or toward the extraction plate **805**. In some instances, the deflection electrode **802** may be configured to move even below the extraction plate **805**. The deflection electrode **802** and inner portions **807***a* and **807***b* of extraction plate **805** may be coupled to voltage sources (not shown) to vary voltage to either deflection electrode **802** or extraction plate **805**, as described above with respect to FIGS. **6**A-**6**D.

As noted above with respect to FIGS. **4**A and **4**B, the motion of a deflection electrode may generate changes in ion trajectories for ions extracted from a plasma, such as plasma **808**. In the processing apparatus **800** of FIG. **8**A, the deflection electrode **802** may be moved with respect to the extraction plate **805** while voltages applied to deflection electrode **802** and inner portions **807***a*, **807***b* remain constant. This motion in itself may vary the shape of the plasma menisci **810** and **811**. However, in other embodiments, voltage applied to the deflection electrode **802** or inner portions **807***a* and **807***b* may be varied in conjunction with movement of the deflection electrode **802** along the axis **809**. Such coupled changes in voltage applied to extraction components with movement of the deflection electrode **802** provides further control over mean ion angle and ion angular distribution for ions extracted from the plasma **808**.

According to other embodiments the deflection electrode may be composed of two parts, deflection electrode parts **822***a* and **822***b* as shown in FIG. **8**B. In FIG. **8**B, a portion of a processing apparatus **820** is illustrated showing an extraction plate **825** composed of electrically non-conductive parts **826***a* and **826***b* and electrically conductive parts, inner portions **827***a* and **827***b*. These parts can move independently along the axis **829**, which is parallel with the Oz axis of the Cartesian coordinate system. By changing the relative positions of the deflection electrode parts **822***a* and **822***b* with respect to the inner portions **827***a* and **827***b* of an extraction plate **825**, the shape of plasma menisci **830** and **831** may be changed, resulting in different ion mean angle and angular distributions of the extracted ion beamlets. In addition, the bias voltages applied to the deflection electrode parts **822***a* and **822***b* or applied to inner portions **807***a* and **807***b* may be varied in conjunction with movement of the deflection electrode parts **822***a* and **822***b* along the axis **809**. Such coupled changes in bias voltages applied to extraction components with movement of the deflection electrode parts **822***a* and **822***b* provides further control over mean ion angle and ion angular distribution for ions extracted from the plasma **808**.

FIG. **8**C provides an example of a processing apparatus **840** that includes an extraction plate **845** composed of electrically non-conductive parts, outer portions **846***a* and **846***b* and electrically conductive parts, inner portions **847***a* and **847***b*. The extraction plate has independently movable portions, shown as portion **852**, composed of outer portion **846***a* and inner portion **847***a*, and portion **854**, composed of outer portion **846***b* and inner portion **847***b*. The portion **852** and portion **854** are each movable along an axis **849** that lies parallel to the Y-axis. When moving in opposite directions along the axis **849** the portions **852** and **854** may increase or decrease the width of the extraction plate aperture. This change in width serves to change the shape and position of plasma menisci **850** and **851** that form between the deflection electrode **842** and inner portions **847***a* and **847***b*, respectively, of the extraction plate **845**.

FIG. **8**D presents a further embodiment of a processing apparatus **860** in which an extraction plate **866** includes independently movable portions, shown as portion **863** and **865**. The portion **863** and portion **865** are each movable along an axis **869** that lies parallel to the Z-axis. As illustrated in FIG. **8**D this motion allows the extraction plate **866** to assume a staggered configuration in which movement of the portions **863** and **865** with respect to one another causes them to be positioned in different planes P**1**, P**2** where each plane may be parallel to the X-Y plane. In the example illustrated, this results in two different plasma menisci, shown as plasma menisci **870**, **871**, which differ from one another in shape. The difference in shape is effective to generate different mean angles in ion beams (not shown) that are extracted from plasma **808** via the plasma menisci **870**, **871** when an extraction voltage is applied. It is also notable that the plasma meniscus adjacent the lower portion, such as plasma meniscus **871**, may be oriented more vertically and produce a mean angle that has a higher deviation from perpendicular to the plane P**2**. In various embodiments a single processing system may incorporate the movement capability of the various extraction components exhibited in FIGS. **8**A-**8**D. Thus, an extraction system may provide motion of separate parts of deflection electrode with respect to an extraction plate as well as relative motion of separate portions of an extraction plate with respect to one another in two orthogonal directions.

In various additional embodiments an extraction plate may include multiple apertures in which at least one aperture includes a deflection electrode. FIG. **9** depicts a portion of a processing apparatus **900** that includes an extraction plate **910** provided with three apertures, apertures **904**, **914**, and **924**. Deflection electrodes **902**, **912**, and **922** are located proximate apertures **904**, **914**, and **924**, respectively. In various embodiments, deflection electrodes **902**, **912**, and **922** may each be provided with a separate voltage source that allows independent control of voltage, shown as voltages V_1, V_2, and V_3 for simplicity. When an extraction voltage is applied between the plasma and the substrate **930**, this may allow the extraction plate **910** to extract simultaneously from plasma **908** three different sets of ion beams **906**, **916**, and **926**, where mean angle is varied between the different sets of ion beams as illustrated. This may be useful for providing ions having different incidence angles to a substrate **930** when the substrate is scanned along the axis **940** in a single pass under all of the apertures, **904**, **914**, **924**. It is to be noted that in various additional embodiments, in multiple aperture extraction plates, the position of deflection electrodes with respect to respective apertures may be adjustable, as well as the width of apertures, and the relative position of different extraction plate portions along the Z-axis direction, as highlighted in FIGS. **8**A-**8**D.

FIG. **10** depicts a portion of a processing apparatus **1000** according to another embodiment that includes an extraction plate **910** provided with three apertures, apertures **904**, **1014**, and **1024**. Deflection electrodes **902**, and **1012**, are located proximate apertures **904**, **1014**, respectively, as in the embodiment of FIG. **9**, except the fact that deflection electrode **1012** is located outside the plasma chamber (not shown). By placing the deflection electrode **1012** in the proximity of the aperture **1014** but outside the plasma chamber allows extraction of ion beams **1016** with very large mean angles as described in FIG. **2**B. Furthermore, in this embodiment, no deflection electrode is located proximate the aperture **1024**. In this case, a single ion beam ion beam **1026** is extracted from the aperture **1024**. Depending upon the width of the aperture **1024** along the Y-direction, the shape of the meniscus **1025** may vary. In the example shown in FIG. **10**, resultant ion trajectories of an ion beam **1026** that is extracted from plasma **1008** through aperture **1024** are aligned closely with the Z-axis so that the ion beam **1026** strikes the substrate **930** at nearly perpendicular incidence. The combination of ion trajectories provided by the extraction plate **910** may be particularly useful for treating certain features of a substrate, such as relief features **1010**. As shown in FIG. **10**, the processing apparatus **1000** generates ion beams **906**,**1016**,**1026** that strike both sidewalls **1030**, **1050** and horizontal surfaces

1040 of each relief feature 1010 when the substrate 930 is scanned along the axis 940 in a back-and-forth pass.

The present disclosure is not to be limited in scope by the specific embodiments described herein. Indeed, other various embodiments of and modifications to the present disclosure, in addition to those described herein, will be apparent to those of ordinary skill in the art from the foregoing description and accompanying drawings. Thus, such other embodiments and modifications are intended to fall within the scope of the present disclosure. Furthermore, although the present disclosure has been described herein in the context of a particular implementation in a particular environment for a particular purpose, those of ordinary skill in the art will recognize that its usefulness is not limited thereto and that the present disclosure may be beneficially implemented in any number of environments for any number of purposes. Accordingly, the claims set forth below should be construed in view of the full breadth and spirit of the present disclosure as described herein.

What is claimed is:

1. A processing apparatus comprising:

a plasma source coupled to a plasma chamber to generate a plasma in the plasma chamber;

an extraction plate disposed along a side of the plasma chamber, the extraction plate having an aperture;

a deflection electrode disposed proximate the aperture and configured to define a pair of plasma menisci when the plasma is present in the plasma chamber, wherein the deflection electrode includes a first deflection electrode part adjacent a second deflection electrode part, and wherein the first deflection electrode part and the second deflection electrode part are each independently movable in a vertical direction; and

a deflection electrode power supply to apply a bias voltage to the deflection electrode with respect to the plasma, wherein a first bias voltage applied to the deflection electrode is configured to generate a first angle of incidence for ions extracted through the aperture from the plasma, and a second bias voltage applied to the deflection electrode is configured to generate a second angle of incidence of ions extracted through the aperture from the plasma, the second angle of incidence being different from the first angle of incidence.

2. The processing apparatus of claim **1**, wherein the pair of plasma menisci have a first shape when the first bias voltage is applied to the deflection electrode, and wherein the pair of plasma menisci have a second shape different from the first shape when the second bias voltage is applied to the deflection electrode.

3. The processing apparatus of claim **1**, wherein the deflection electrode is configured to move in a direction perpendicular to a plane defined by a plane of the extraction plate, wherein in a first deflection electrode position a first distance from the plane, ions extracted from the plasma have first angular incidence, and wherein in a second deflection electrode position a second distance from the plane, wherein the second distance is greater than the first distance, ions extracted from the plasma have a second angular incidence different from the first angular incidence.

4. The processing apparatus of claim **1**, further comprising an extraction plate power supply configured to apply an extraction plate voltage to the extraction plate independently of the bias voltage applied to the deflection electrode.

5. The processing apparatus of claim **1**, wherein the extraction plate includes a first portion and second portion and defines a plane, the processing apparatus further comprising a first extraction plate power supply configured to supply a first bias voltage to the first portion, and a second extraction plate power supply configured to supply a second bias voltage to the second portion.

6. The processing apparatus of claim **1**, wherein the deflection electrode power supply is interoperative with the deflection electrode to vary angle of incidence of ions extracted from at least one of the pair of plasma meniscus by ten degrees or greater when the bias voltage applied to the deflection electrode is varied.

7. The processing apparatus of claim **5**, wherein the aperture comprises a first aperture and the deflection electrode comprises a first deflection electrode, and wherein the extraction plate comprises a third portion disposed adjacent the second portion and configured to define a second aperture therebetween.

8. The processing apparatus of claim **7**, wherein the pair of plasma menisci comprises a first pair, the process apparatus further comprising a second deflection electrode disposed adjacent to the second aperture and configured to generate a second pair of plasma menisci proximate the second aperture.

9. The processing apparatus of claim **1**, wherein the deflection electrode is configured to vary meniscus shape of the pair of plasma menisci when power from the plasma source is varied over a plasma power range, wherein angle of incidence of ions extracted through the pair of plasma menisci varies by at least ten degrees.

10. A processing apparatus comprising:

a plasma source coupled to a plasma chamber to generate a plasma in the plasma chamber;

a process chamber adjacent the plasma chamber and containing a substrate holder;

an extraction system disposed between the plasma and substrate holder, the extraction system comprising a deflection electrode and an extraction plate having an aperture that is disposed proximate the deflection electrode,

wherein the deflection electrode includes a first deflection electrode part adjacent a second deflection electrode part, the first deflection electrode part and the second deflection electrode part each being independently movable in a vertical direction,

wherein, when an extraction voltage is applied between the plasma chamber and substrate holder, the deflection electrode and extraction plate are interoperative to extract a pair of ion beams from the plasma through the aperture, and

wherein the deflection electrode and extraction plate are interoperative to adjust an angle of incidence of at least one of the pair of ion beams by movement of at least one of the deflection electrode and extraction plate.

11. The processing apparatus of claim **10**, further comprising a deflection electrode power supply to apply a bias voltage to the deflection electrode, wherein a first bias voltage generated by the deflection electrode power supply is configured to generate a first angle of incidence for ions extracted from the plasma, and a second bias voltage generated by the deflection electrode power supply is configured to generate a second angle of incidence of ions extracted through the aperture from the plasma, the second angle of incidence being different from the first angle of incidence.

12. The processing apparatus of claim **11**, wherein the deflection electrode comprises a first deflection electrode part and second deflection electrode part that are electrically conductive and electrically isolated from one another, wherein the deflection electrode power supply is a first deflection electrode power supply, the first electrode part is coupled to the first deflection electrode power supply, the processing apparatus further comprising a second deflection electrode power supply coupled to the second deflection electrode part, wherein the first deflection electrode part and second deflection electrode part are operative receive to bias voltage independently from one another from the respective first and second deflection electrode bias supplies.

13. A method of controlling an ion beam provided to a substrate, comprising:

generating a plasma in a plasma chamber adjacent a process chamber that contains the substrate;

providing an extraction plate having an aperture between the plasma chamber and process chamber;

arranging a deflection electrode proximate the aperture, wherein the deflection electrode includes a first deflection electrode part adjacent a second deflection electrode part, and wherein the first deflection electrode part and the second deflection electrode part are each independently movable in a vertical direction; and

varying a deflection electrode voltage applied to the deflection electrode from a first voltage to a second voltage, wherein the first voltage is configured to generate a first angle of incidence for ions extracted from the plasma, and second voltage is configured to generate a second angle of incidence of ions extracted through the aperture from the plasma, the second angle of incidence being different from the first angle of incidence.

14. The method of claim **13**, further comprising moving the deflection electrode in a direction perpendicularly to a plane of the extraction plate from a first deflection electrode position nearer the extraction plate to a second deflection electrode position more remote from the substrate,

wherein ions extracted from the plasma at the first deflection electrode position have a first angular incidence and wherein ions extracted from the plasma have a second angular incidence different from the first angular incidence.

15. The method of claim **13**, wherein the extraction plate includes a first portion and second portion that define a first plane, the method further comprising moving the first portion with respect to the second portion within the first plane so as to vary a width of the aperture.

* * * * *