US 20100255683A1

(19) **United States**

(12) **Patent Application Publication**

(10) **Pub. No.: US 2010/0255683 A1**

(43) **Pub. Date: Oct. 7, 2010**

GODET et al.

(54) **PLASMA PROCESSING APPARATUS**

(75) Inventors: **Ludovic GODET**, North Reading, MA (US); **Timothy J. Miller**, Ipswich, MA (US); **Christopher J. Leavitt**, Gloucester, MA (US); **Bernard G. Lindsay**, Danvers, MA (US)

Correspondence Address:
VARIAN SEMICONDUCTOR EQUIPMENT ASSC., INC.
35 DORY RD.
GLOUCESTER, MA 01930-2297 (US)

(73) Assignee: **VARIAN SEMICONDUCTOR EQUIPMENT ASSOCIATES**, Gloucester, MA (US)

(21) Appl. No.: **12/418,120**

(22) Filed: **Apr. 3, 2009**

Publication Classification

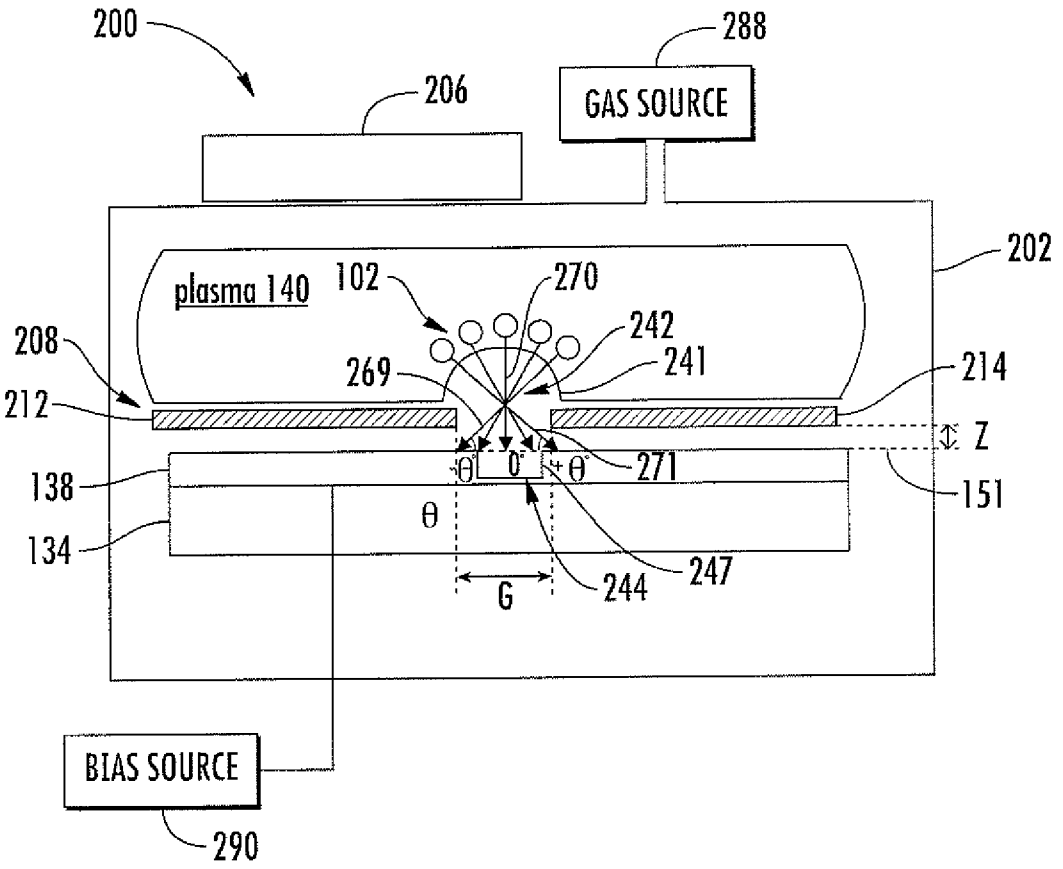
(51) **Int. Cl.**

H01L 21/3065	(2006.01)
C23C 16/513	(2006.01)
H01L 21/306	(2006.01)
H01L 21/302	(2006.01)

(52) **U.S. Cl.** ..... **438/710**; 118/723 R; 156/345.1; 438/758; 257/E21.218; 257/E21.214

(57) **ABSTRACT**

A plasma processing apparatus includes a process chamber, a platen positioned in the process chamber for supporting a workpiece, a source configured to generate a plasma in the process chamber having a plasma sheath adjacent to the front surface of the workpiece, and an insulating modifier. The insulting modifier is configured to control a shape of a boundary between the plasma and the plasma sheath so a portion of the shape of the boundary is not parallel to a plane defined by a front surface of the workpiece facing the plasma. Controlling the shape of the boundary between the plasma and the plasma sheath enables a large range of incident angles of particles striking the workpiece to be achieved.



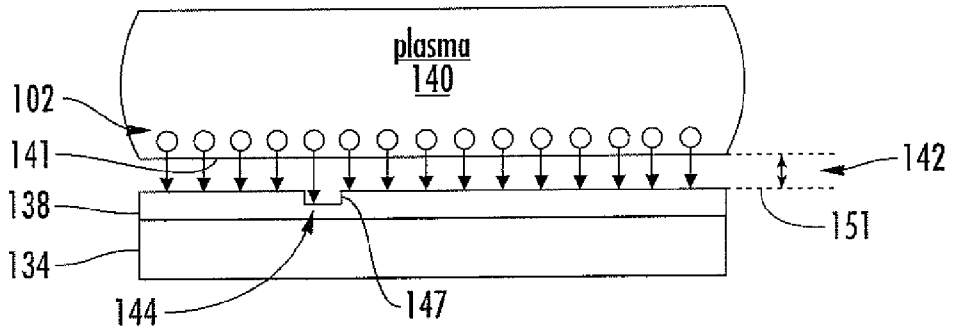


FIG. 1
(PRIOR ART)

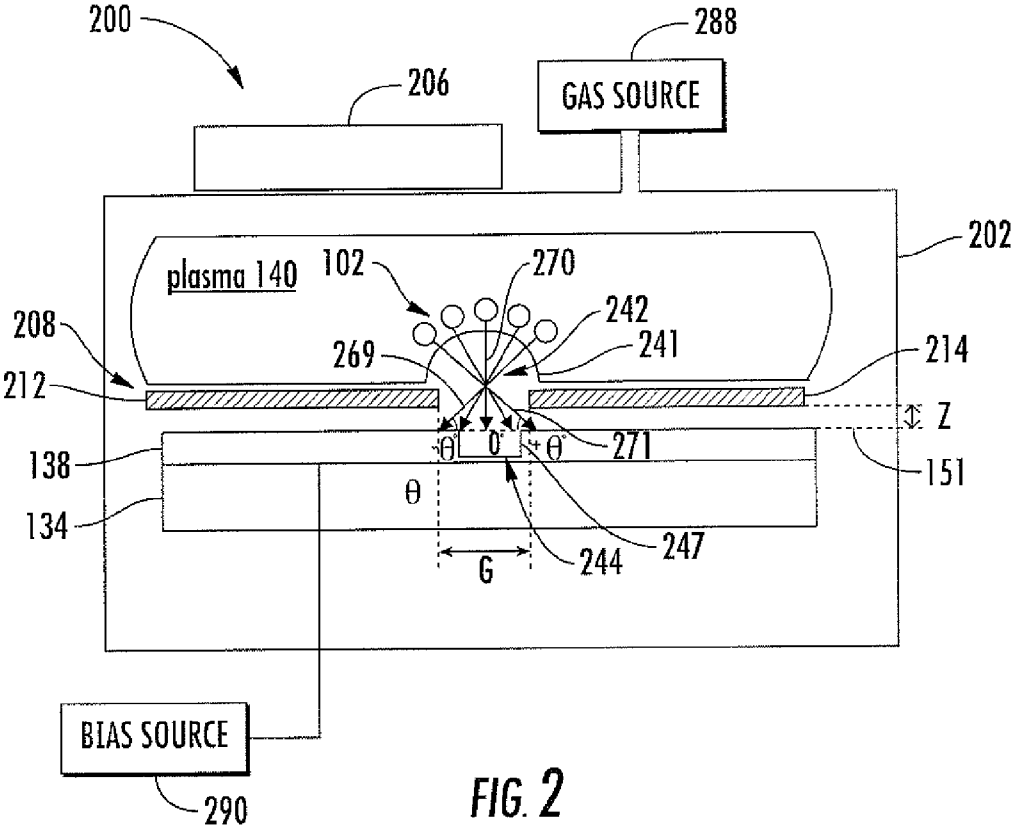


FIG. 2

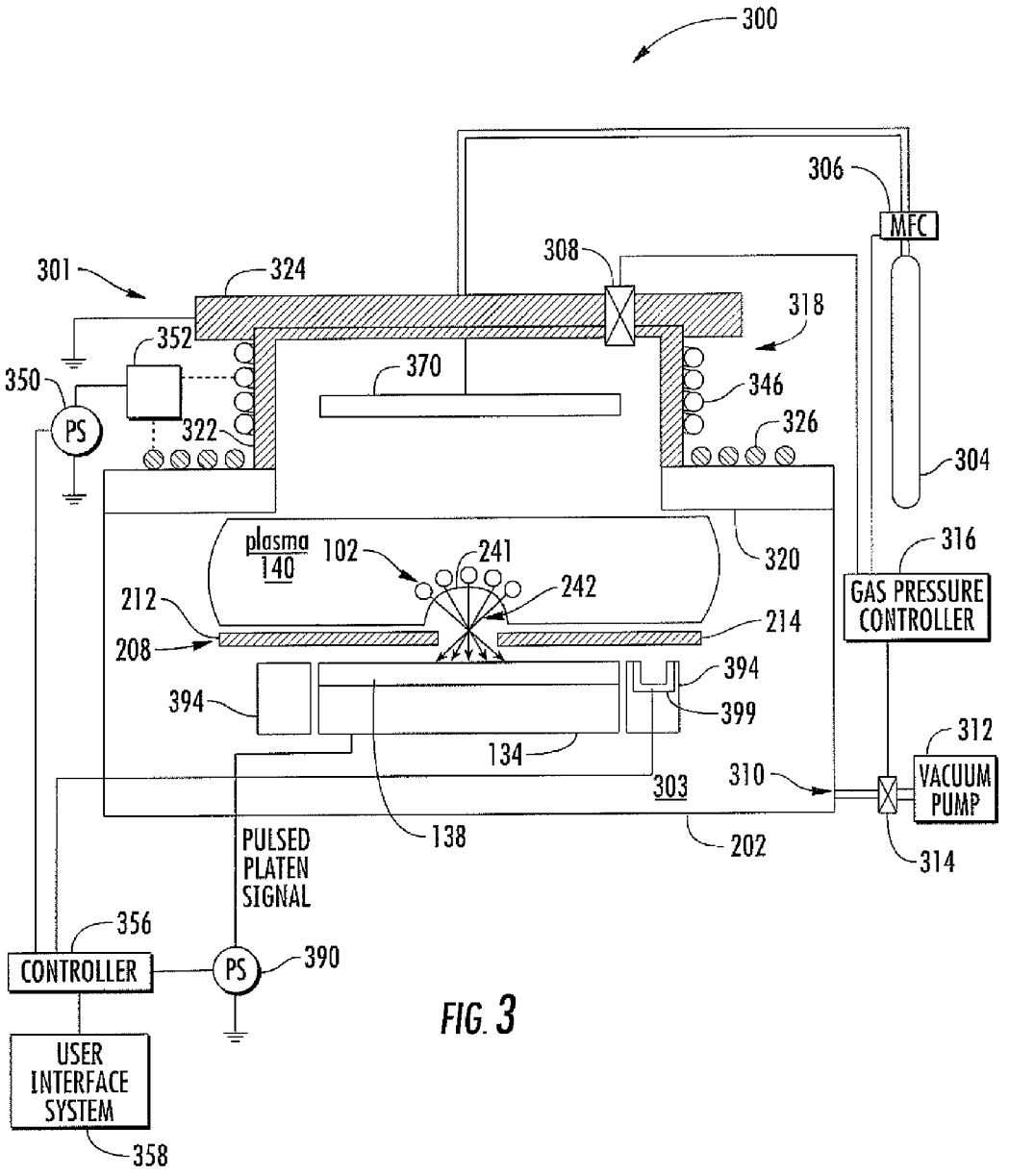

300
306
MFC
308
301
324
318
352
370
350
346
PS
322
326
304
plasma
140
102
241
242
320
316
GAS PRESSURE
CONTROLLER
212
214
208
394
394
399
312
134
303
310
VACUUM
PUMP
PULSED
PLATEN
SIGNAL
138
202
314
356
CONTROLLER
PS
390
USER
INTERFACE
SYSTEM
358

FIG. 3

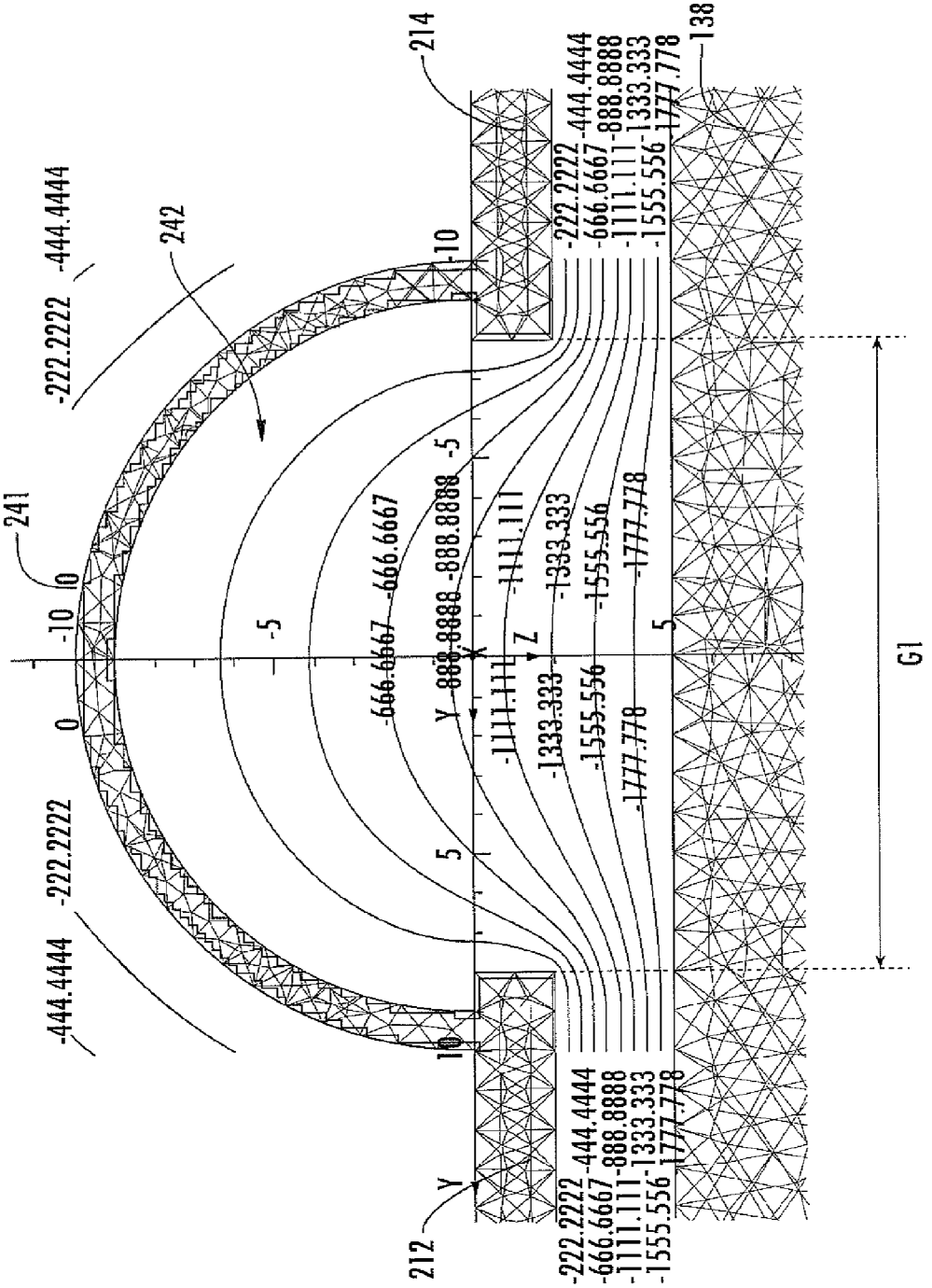

241
242
214
138
212
-222.2222
-444.4444
-666.6667
-888.8888
-1111.111
-1333.333
-1555.556
-1777.778
-10
-5
0
5
10
Z
Y
G1

FIG. 4

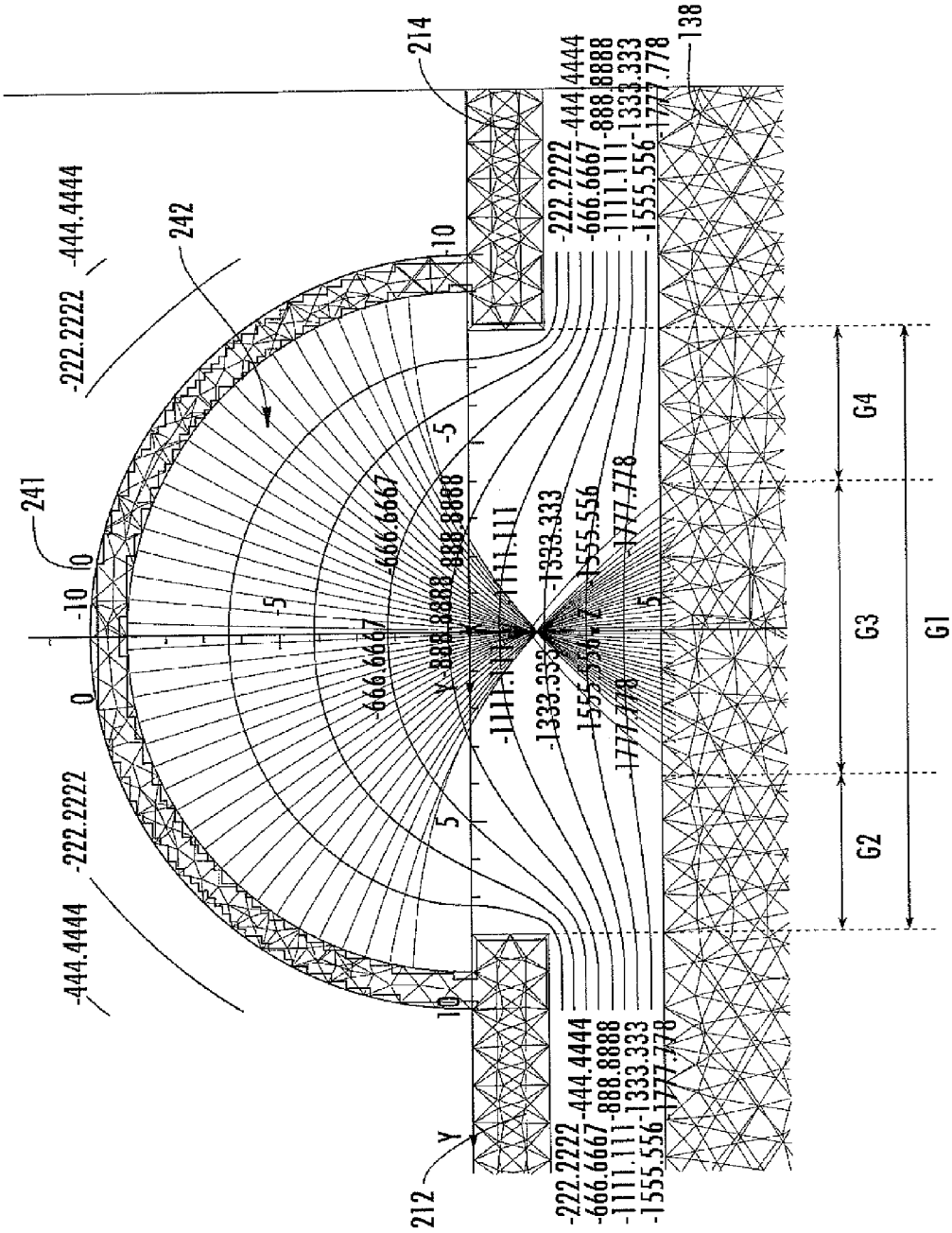

214
138
242
241
212
Y
-444.4444
-222.2222
0
222.2222
444.4444
-10
-5
5
10
-222.2222
-444.4444
-666.6667
-888.8888
-1111.111
-1333.333
-1555.556
-1777.778
G1
G2
G3
G4

FIG. 5

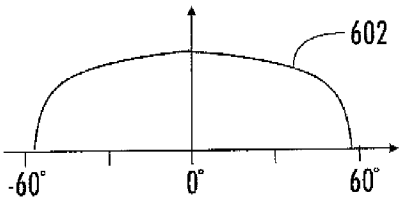


FIG. 6

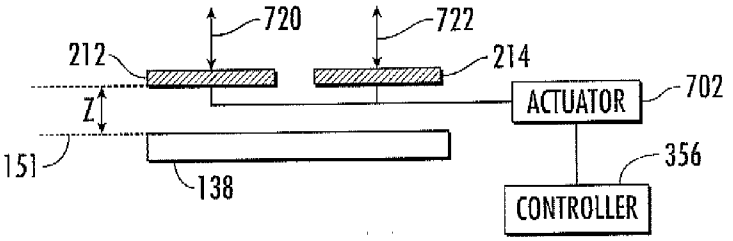


FIG. 7

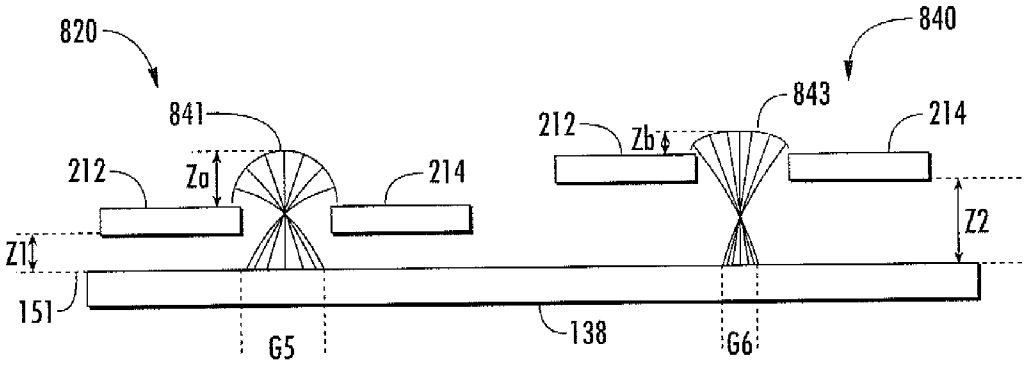


FIG. 8

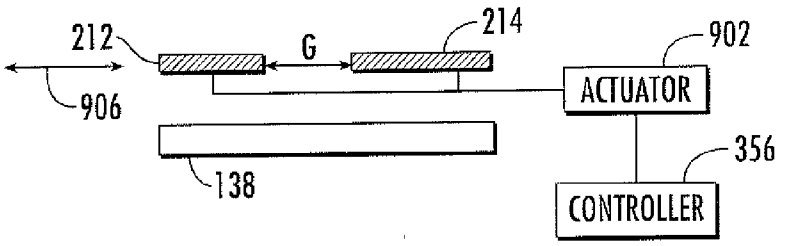

212
G
214
902
906
ACTUATOR
356
138
CONTROLLER

FIG. 9

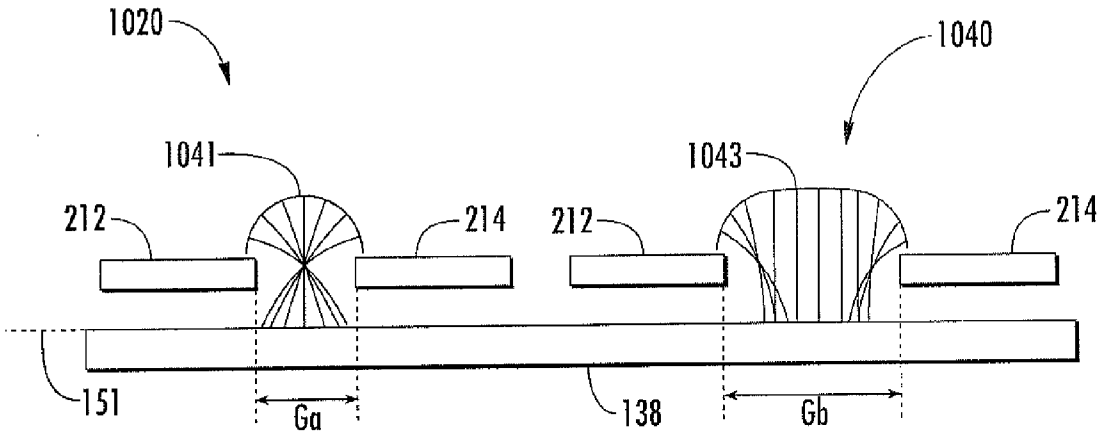

1020
1040
1041
1043
212
214
212
214
151
Ga
138
Gb

FIG. 10

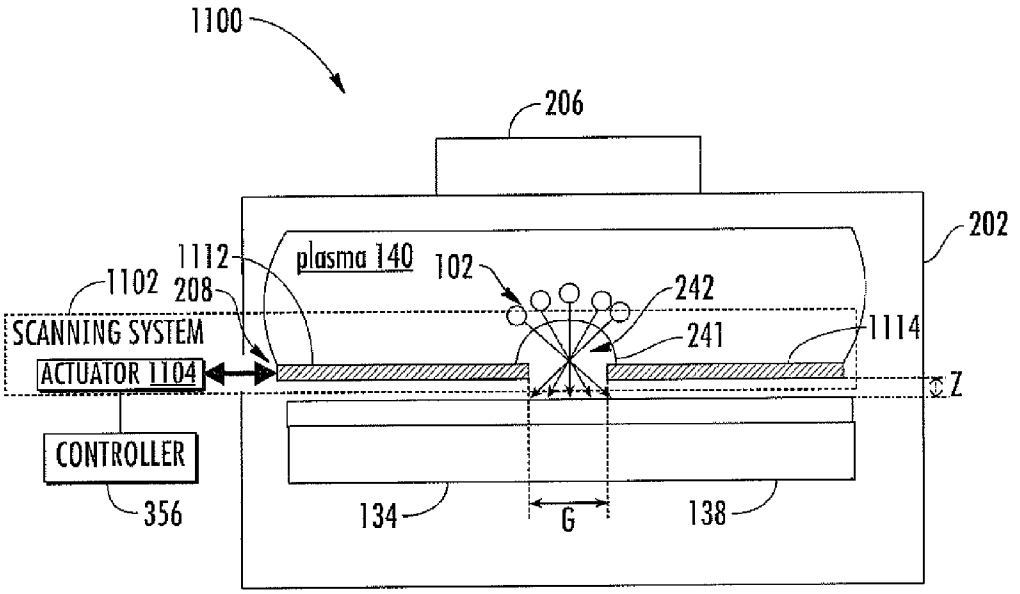

1100
206
202
1112
plasma 140
102
1102
208
242
241
1114
SCANNING SYSTEM
ACTUATOR 1104
Z
CONTROLLER
356
134
G
138

FIG. 11

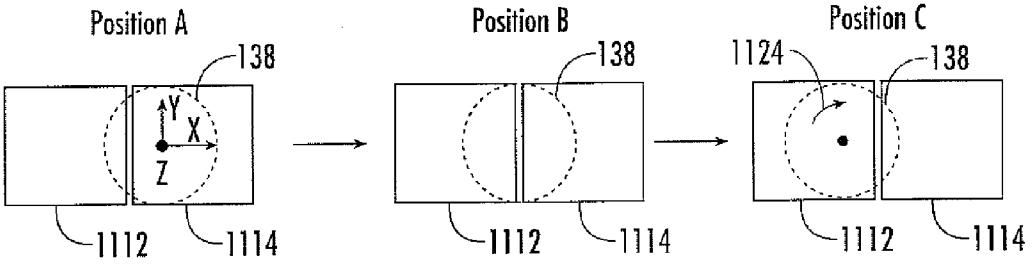

Position A
Position B
Position C
138
138
1124
138
Y
X
Z
1112
1114
1112
1114
1112
1114

FIG. 12

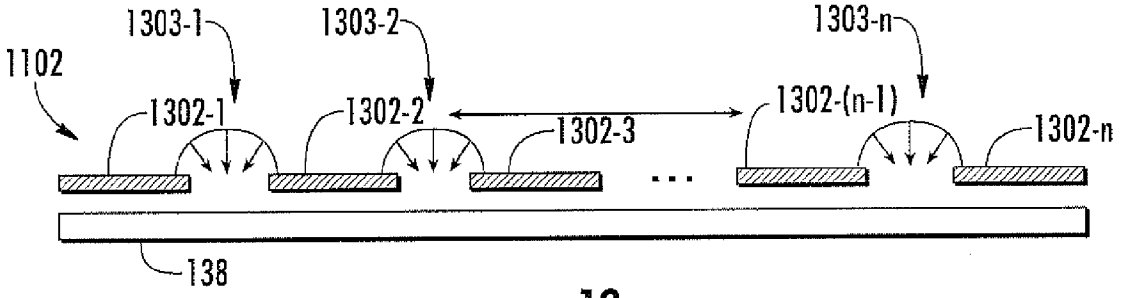


FIG. 13

PLASMA PROCESSING APPARATUS

CROSS REFERENCE TO RELATED APPLICATIONS

[0001] This application is related to U.S. application Ser. No. 12/417,929 filed Apr. 3, 2009, which is incorporated herein by reference.

FIELD

[0002] This disclosure relates to plasma processing, and more particularly to a plasma processing apparatus.

BACKGROUND

[0003] A plasma processing apparatus generates a plasma in a process chamber for treating a workpiece supported by a platen in the process chamber. A plasma processing apparatus may include, but not be limited to, doping systems, etching systems, and deposition systems. The plasma is generally a quasi-neutral collection of ions (usually having a positive charge) and electrons (having a negative charge). The plasma has an electric field of about 0 volts per centimeter in the bulk of the plasma. In some plasma processing apparatus, ions from the plasma are attracted towards a workpiece. In a plasma doping apparatus, ions may be attracted with sufficient energy to be implanted into the physical structure of the workpiece, e.g., a semiconductor substrate in one instance.

[0004] The plasma is bounded by a region proximate the workpiece generally referred to as a plasma sheath. The plasma sheath is a region that has fewer electrons than the plasma. The light emission from this plasma sheath is less intense than the plasma since fewer electrons are present and hence few excitation-relaxation collisions occur. Hence, the plasma sheath is sometimes referred to as "dark space."

[0005] Turning to FIG. **1**, a cross sectional view of portions of a known plasma processing apparatus is illustrated where a plasma **140** has a plasma sheath **142** adjacent to a front surface of a workpiece **138** to be treated. The front surface of the workpiece **138** defines a plane **151**, and the workpiece **138** is supported by a platen **134**. The boundary **141** between the plasma **140** and the plasma sheath **142** is parallel to the plane **151**. Ions **102** from the plasma **140** may be attracted across the plasma sheath **142** towards the workpiece **138**. Accordingly, the ions **102** that are accelerated towards the workpiece **138** generally strike the workpiece **138** at about a 0° angle of incidence relative to the plane **151** (e.g., perpendicular to the plane **151**). There can be a small angular spread of the angle of incidence of less than about 3°. In addition, by controlling plasma process parameters such as gas pressure within a process chamber, the angular spread may be increased up to about 5°.

[0006] A drawback with conventional plasma processing is the lack of angular spread control of the ions **102**. As structures on the workpiece become smaller and as three dimensional structures become more common (e.g., trench capacitors, vertical channel transistors such as FinFETs) it would be beneficial to have greater angle control. For example, a trench **144** having an exaggerated size for clarity of illustration is shown in FIG. **1**. With ions **102** being directed at about a 0° angle of incidence or an even angular spread up to 5°, it can be difficult to uniformly treat the sidewalls **147** of the trench **144**.

[0007] Accordingly, there is a need for a plasma processing apparatus which overcomes the above-described inadequacies and shortcomings.

SUMMARY

[0008] According to a first aspect of the disclosure, a plasma processing apparatus is provided. The plasma processing apparatus includes a process chamber, a platen positioned in the process chamber for supporting a workpiece, a source configured to generate a plasma in the process chamber having a plasma sheath adjacent to the front surface of the workpiece, and an insulating modifier. The insulating modifier is configured to control a shape of a boundary between the plasma and the plasma sheath so a portion of the shape of the boundary is not parallel to a plane defined by a front surface of the workpiece facing the plasma

[0009] According to another aspect of the disclosure, a method is provided. The method includes positioning a workpiece in a process chamber, generating a plasma in the process chamber having a plasma sheath adjacent to the front surface of the workpiece, and modifying a shape of a boundary between the plasma and the plasma sheath with an insulating modifier so a portion of the shape of the boundary is not parallel to a plane defined by a front surface of the workpiece facing the plasma.

BRIEF DESCRIPTION OF THE DRAWINGS

[0010] For a better understanding of the present disclosure, reference is made to the accompanying drawings, in which like elements are referenced with like numerals, and in which:

[0011] FIG. **1** is a simplified block diagram of a conventional plasma processing apparatus consistent with the prior art;

[0012] FIG. **2** is a block diagram of a plasma processing apparatus consistent with an embodiment of the disclosure;

[0013] FIG. **3** is a block diagram of a plasma doping apparatus consistent with an embodiment of the disclosure;

[0014] FIG. **4** is a cross sectional view of a pair of insulators to control a shape of a boundary between a plasma and a plasma sheath;

[0015] FIG. **5** is a cross sectional view consistent with FIG. **4** illustrating ion trajectories of ions accelerated across the boundary of FIG. **4**;

[0016] FIG. **6** is a plot of angular ion distributions of the ion trajectories of FIG. **5**;

[0017] FIG. **7** is a block diagram of a system to control a vertical spacing between a pair of insulators and a workpiece;

[0018] FIG. **8** is a cross sectional view consistent with FIG. **7** illustrating ion trajectories at differing vertical spacing;

[0019] FIG. **9** is a block diagram of a system to control a horizontal spacing between a pair of insulators;

[0020] FIG. **10** is a cross sectional view consistent with FIG. **9** to illustrating ion is trajectories at differing horizontal spacing;

[0021] FIG. **11** is a block diagram of a plasma processing apparatus having a scanning system to move a pair of insulating sheets relative to a workpiece;

[0022] FIG. **12** is a plan view of the insulating sheets of FIG. **11** showing relative movement between the insulating sheets and a disk shaped workpiece; and

[0023] FIG. **13** is a block diagram of a scanning system consistent with FIG. **11** having a plurality of insulators.

DETAILED DESCRIPTION

[0024] FIG. **2** is a block diagram of one plasma processing apparatus **200** having an insulating modifier **208** consistent with an embodiment of the disclosure. The insulating modifier **208** is configured to modify an electric field within the plasma sheath **242** to control a shape of a boundary **241** between the plasma **140** and the plasma sheath **242**. Accordingly, ions **102** that are attracted from the plasma **140** across the plasma sheath **242** may strike the workpiece **138** at a large range of incident angles.

[0025] The plasma processing apparatus **200** may be further described herein as a plasma doping apparatus. However, the plasma processing apparatus **200** may also include, but not be limited to, etching and deposition systems. Furthermore, a plasma doping system can perform many differing material modification processes on a treated workpiece. One such process includes doping a workpiece, such as a semiconductor substrate, with a desired dopant.

[0026] The plasma processing apparatus **200** may include a process chamber **202**, a platen **134**, a source **206**, and the insulating modifier **208**. The platen **134** is positioned in the process chamber **202** for supporting the workpiece **138**. The workpiece may include, but not be limited to, a semiconductor wafer, flat panel, solar panel, and polymer substrate. The semiconductor wafer may have a disk shape with a diameter of 300 millimeters (mm) in one embodiment. The source **206** is configured to generate the plasma **140** in the process chamber **202** as is known in the art. In the embodiment of FIG. **2**, the insulting modifier **208** includes a pair of insulators **212** and **214** defining a gap there between having a horizontal spacing (G). In other embodiments, the insulating modifier may include only one insulator. The pair of insulators **212** and **214** may be a pair of sheets having a thin, flat shape. In other embodiments, the pair of insulators **212** and **214** may be other shapes such as tube shaped, wedge shaped, and/or have a beveled edge proximate the gap.

[0027] In one embodiment, the horizontal spacing of the gap defined by the pair of insulators **212** and **214** may be about 6.0 millimeters (mm). The pair of insulators **212** and **214** may also be positioned a vertical spacing (Z) above the plane **151** defined by the front surface of the workpiece **138**. In one embodiment, the vertical spacing (Z) may be about 3.0 mm.

[0028] In operation, a gas source **288** supplies an ionizable gas to the process chamber **202**. Examples of an ionizable gas include, but are not limited to, BF_3, BI_3, N_2, Ar, PH_3, AsH_3, B_2H_6, H_2, Xe, Kr, Ne, He, SiH_4, SiF_4, GeH_4, GeF_4, CH_4, CF_4, AsF_5, PF_3, and PF_5. The source **206** may generate the plasma **140** by exciting and ionizing the gas provided to the process chamber **202**. Ions may be attracted from the plasma **140** across the plasma sheath **242** by different mechanisms. In the embodiment of FIG. **2**, the bias source **290** is configured to bias the workpiece **138** to attract ions **102** from the plasma **140** across the plasma sheath **242**. The bias source **290** may be a DC power supply to provide a DC voltage bias signal or an RF power supply to provide an RF bias signal.

[0029] Advantageously, the insulating modifier **208** modifies the electric field is within the plasma sheath **242** to control a shape of the boundary **241** between the plasma **140** and the plasma sheath **242**. In the embodiment of FIG. **2**, the insulating modifier **208** includes a pair of insulators **212** and **214**. The insulators **212**, **214** may be fabricated of quartz, alumina, boron nitride, glass, silicon nitride, etc. The boundary **241** between the plasma **140** and the plasma sheath **242** may have a convex shape relative to the plane **151**. When the bias source **290** biases the workpiece **138**, ions **102** are attracted across the plasma sheath **242** through the gap between the insulators **212** and **214** at a large range of incident angles. For instance, ions following trajectory path **271** may strike the workpiece **138** at an angle of $+\theta°$ relative to the plane **151**. Ions following trajectory path **270** may strike the workpiece **138** at about an angle of 0° relative to the same plane **151**.

[0030] Ions following trajectory path **269** may strike the workpiece **138** an angle of $-\theta°$relative to the plane **151**. Accordingly, the range of incident angles may be between $+\theta°$ and $-\theta°$ centered about 0°. In addition, some ion trajectories paths such as paths **269** and **271** may cross each other. Depending on a number of factors including, but not limited to, the horizontal spacing (G) between the insulators **212** and **214**, the vertical spacing (Z) of the insulators above the plane **151**, the dielectric constant of the insulators **212** and **214**, and other plasma process parameters, the range of incident angles (θ) may be between +60° and −60° centered about 0°. Hence, small three dimensional structures on the workpiece **138** may be treated uniformly by the ions **102**. For example, the sidewalls **247** of the trench **244** having an exaggerated size for clarity of illustration may be more uniformly treated by the ions **102** compared to that of FIG. **1**.

[0031] Turning to FIG. **3**, a block diagram of one exemplary plasma doping apparatus **300** is illustrated. Consistent with the apparatus of FIG. **2**, the plasma doping apparatus **300** has the pair of insulators **212** and **214** to control a shape of the boundary **241** between the plasma **140** and the plasma sheath **242**.

[0032] The plasma doping apparatus **300** includes a process chamber **202** defining an enclosed volume **303**. A gas source **304** provides a primary dopant gas to the enclosed volume **303** of the process chamber **302** through the mass flow controller **306**. A gas baffle **370** may be positioned in the process chamber **202** to deflect the flow of gas from the gas source **304**. A pressure gauge **308** measures the pressure inside the process chamber **202**. A vacuum pump **312** evacuates exhausts from the process chamber **202** through an exhaust port **310**. An exhaust valve **314** controls the exhaust conductance through the exhaust port **310**.

[0033] The plasma doping apparatus **300** may further includes a gas pressure controller **316** that is electrically connected to the mass flow controller **306**, the pressure gauge **308**, and the exhaust valve **314**. The gas pressure controller **316** may be configured to maintain a desired pressure in the process chamber **202** by controlling either the exhaust conductance with the exhaust valve **314** or a process gas flow rate with the mass flow controller **306** in a feedback loop that is responsive to the pressure gauge **308**.

[0034] The process chamber **202** may have a chamber top **318** that includes a first section **320** formed of a dielectric material that extends in a generally horizontal direction. The chamber top **318** also includes a second section **322** formed of a dielectric material that extends a height from the first section **320** in a generally vertical direction. The chamber top **318** further includes a lid **324** formed of an electrically and thermally conductive material that extends across the second section **322** in a horizontal direction.

[0035] The plasma doping apparatus further includes a source **301** configured to generate a plasma **140** within the

process chamber **202**. The source **301** may include a RF source **350** such as a power supply to supply RF power to either one or both of the planar antenna **326** and the helical antenna **346** to generate the plasma **140**. The RF source **350** may be coupled to the antennas **326**, **346** by an impedance matching network **352** that matches the output impedance of the RF source **350** to the impedance of the RF antennas **326**, **346** in order to maximize the power transferred from the RF source **350** to the RF antennas **326**, **346**. The plasma doping apparatus may also include a bias power supply **390** electrically coupled to the platen **134**. The plasma doping system may further include a controller **356** and a user interface system **358**. The controller **356** can be or include a general-purpose computer or network of general-purpose computers that may be programmed to perform desired input/output functions. The controller **356** may also include communication devices, data storage devices, and software. The user interface system **358** may include devices such as touch screens, keyboards, user pointing devices, displays, printers, etc. to allow a user to input commands and/or data and/or to monitor the plasma doping apparatus via the controller **356**. A shield ring **394** may be disposed around the platen **134** to improve the uniformity of implanted ion distribution near the edge of the workpiece **138**. One or more Faraday sensors such as Faraday cup **399** may also be positioned in the shield ring **394** to sense ion beam current.

[0036] In operation, the gas source **304** supplies a primary dopant gas containing a desired dopant for implantation into the workpiece **138**. The source **301** is configured to generate the plasma **140** within the process chamber **302**. The source **301** may be controlled by the controller **356**. To generate the plasma **140**, the RF source **350** resonates RF currents in at least one of the RF antennas **326**, **346** to produce an oscillating magnetic field. The oscillating magnetic field induces RF currents into the process chamber **202**. The RF currents in the process chamber **202** excite and ionize the primary dopant gas to generate the plasma **140**.

[0037] The bias power supply **390** provides a pulsed platen signal having a pulse ON and OFF periods to bias the platen **134** and hence the workpiece **138** to accelerate ions from the plasma **140** towards the workpiece **138** across the plasma sheath **242**. The ions **102** may be positively charged ions and hence the pulse ON periods of the pulsed platen signal may be negative voltage pulses with respect to the process chamber **202** to attract the positively charged ions **102**. The frequency of the pulsed platen signal and/or the duty cycle of the pulses may be selected to provide a desired dose rate. The amplitude of the pulsed platen signal may be selected to provide a desired energy.

[0038] Advantageously, the pair of insulators **212** and **214** controls the shape of the boundary **241** between the plasma **140** and the plasma sheath **242** as previously detailed with respect to FIG. **2**. Therefore, the ions **102** may be attracted across the plasma sheath **242** through the gap between the insulators **212** and **214** at a large range of incident angles for doping the workpiece **138**.

[0039] Turning to FIG. **4**, a partial cross sectional view of the pair of insulators **212** and **214** and workpiece **138** is illustrated showing the electric field lines in the plasma sheath **242** about the gap defined by the insulators **212** and **214**. The electric field lines and resulting arcuate boundary **241** between the plasma and the plasma sheath **242** resulted from a computer simulation with the workpiece **138** biased at −2,000 volts and the insulators **212** and **214** fabricated of glass. As illustrated, the arcuate boundary **241** about the gap may further have a convex to shape relative to the plane **151**.

[0040] FIG. **5** is a cross sectional view consistent with FIG. **4** illustrating simulated ion trajectories accelerated across the plasma sheath **242** through the gap between the insulators **212** and **214**. In a plasma doping apparatus, the ions may be implanted in the workpiece **138** in a central area of the gap spacing due to the shape of the boundary **241** and the electric field lines within the plasma sheath **242**. For instance, of the total horizontal spacing (G**1**) between the insulators **212** and **214**, ions strike the workpiece **138** about the central horizontal spacing (G**3**). No ions strike the workpiece about the peripheral horizontal spacing (G**2**) and (G**4**) proximate the insulators **212** and **214** in this embodiment.

[0041] FIG. **6** is a plot **602** of the distribution of incident angles of ions striking the workpiece **138** consistent with the illustrated ion trajectories of FIG. **5**. As shown, the plot **602** reveals the incident angles are centered about 0° and vary over a large range of angles from about +60° to −60°. This large range of incident angles enables conformal doping of three dimensional structures. For example, the sidewalls of a trench structure may be more uniformly doped with ions having such a large range of incident angles.

[0042] Turning to FIG. **7**, a block diagram of another embodiment consistent with the present disclosure is illustrated where the vertical spacing (Z) between an insulting modifier and the plane **151** defined by the front surface of the workpiece **138** may be adjusted. The insulating modifier may be the pair of insulators **212** and **214** as detailed in other embodiments. An actuator **702** may be mechanically coupled to the pair of insulators **212** and **214** to drive the insulators in a vertical direction as shown by arrows **720**, **722** relative to the plane **151**. The Z position of the pair of insulators **212** and **214** relative to the plane **151**, and also relative to each other, influences the shape of the boundary between the plasma and the plasma sheath and also the trajectories of the ions striking the workpiece **138**. The actuator **702** may be controlled by a controller such as controller **356**.

[0043] FIG. **8** is a cross sectional view consistent with FIG. **7** to illustrate ion trajectories at differing Z positions of the pair of insulators **212** and **214** relative to the plane **151** with all other parameters being equal. In the first relatively short Z gap position **820**, the insulators **212**, **214** are positioned a first distance (Z**1**) above the plane **151**. In a comparatively taller Z gap position **840**, the insulators **212**, **214** are positioned a second distance (Z**2**) above the plane **151**, where (Z**2**)>(Z**1**). In the first position **820**, the boundary **841** between the plasma and the plasma sheath has a convex shape relative to the plane **151**. The boundary **841** also has a shape that approximately approaches the shape of a portion of a circumference of a circle where an apex of the arcuate shape is a distance (Za) above a top surface of the insulator **212**. In contrast, the boundary **843** in the second position **840** has a shallower shape where the apex of the arcuate shape is a shorter distance (Zb) above the top surface of the insulator **212**, or where (Zb)<(Za). The shape of the boundaries **841**, **843** combined with the Z gap distances (Z**1**) and (Z**2**) and the electric field lines in the plasma sheath, influences the angular spread of the ions striking the workpiece **138**. For example, the angular spread of ions striking the workpiece **138** with the relatively short Z gap position **820** is greater than the angular spread of ions striking the workpiece **138** with the relatively longer Z gap position. In addition, ions strike a wider horizontal spacing (G**5**) of the workpiece **138** with the shorter Z gap position

820 compared to the horizontal spacing (G**6**) with the taller Z gap position, where (G**6**)<(G**5**). Although not illustrated in FIG. **8**, the Z gap positions of each insulator **212** and **214** may also be different from each other to further influence the shape of the boundary between the plasma and the plasma sheath and accordingly the angular spread of ions.

[0044] Turning to FIG. **9**, a block diagram of another embodiment consistent with the present disclosure is illustrated where the horizontal spacing (G) between insulators **212** and **214** may be adjusted. The horizontal spacing adjustments may in lieu of, or in addition to, the earlier detailed vertical spacing adjustments of FIGS. **8** and **9**. An actuator **902** may be mechanically coupled to at least one of the pair of insulators **212** and **214** to drive the insulators in the direction shown by the arrow **906** relative to one another. The actuator **902** may be controlled by a controller such as controller **356**.

[0045] FIG. **10** is a cross sectional view consistent with FIG. **9** to illustrate ion trajectories at differing horizontal gap spacing between the insulators **212** and **214** with all other parameters being equal. In the first relatively shorter horizontal gap position **1020**, the insulators **212**, **214** are positioned a first horizontal distance (Ga) from one another. In a comparatively longer horizontal gap position **1040**, the insulators **212**, **214** are positioned a second horizontal distance (Gb) from each other, where (Gb)>(Ga). In the first position **1020**, the boundary **1041** between the plasma and the plasma sheath has a convex shape relative to the plane **151**. The boundary **1041** also has a shape that approximately approaches the shape of a portion of a circumference of a circle. In contrast, the boundary **1043** in the second position **1040** has a convex shape relative to the plane **151** where a central portion of the boundary **1043** is about parallel to the plane **151**. As a result, a larger corresponding central portion of the workpiece **138** is struck with ions having about a 0° angle of incidence relative to the plane **151**.

[0046] FIG. **11** is a block diagram of a plasma processing apparatus **1100** having a scanning system **1102** to drive an insulating modifier **208** relative the workpiece **138**. In the embodiment of FIG. **11**, the insulating modifier **208** includes a pair of square insulating sheets **1112** and **1114** that are best seen in FIG. **12**. The scanning to system **1102** may include an actuator **1104** mechanically coupled to the insulating sheets **1112** and **1114** to drive the same. The actuator **1104** may be controlled by a controller such as controller **356**.

[0047] FIG. **12** is plan view of the square insulating sheets **1112** and **1114** and a disk shaped workpiece **138** to illustrate one example of relative movement between the same. In the embodiment of FIG. **12**, the scanning system **1102** may drive the square insulating sheets **1112** and **1114** from Position A, to Position B, and Position C, etc. so that all portions of the workpiece **138** are exposed to the gap defined by the pair of square insulating sheets **1112** and **1114**. If a Cartesian coordinate system is defined as detailed in FIG. **12**, the insulating sheets **1112** and **1114** are driven in the X direction of FIG. **12**. In other embodiments, the insulating sheets **1112** and **1114** or another set of different insulating sheets may be driven in the Y direction or any angle between the X and Y directions. In addition, the workpiece **138** may be rotated as the scanning system **1102** drives the insulating sheets **1112** and **1114** in one direction. The workpiece **138** may also be rotated by a predetermined rotation angle after the scanning system **1102** drives the insulating sheets in one direction. In one example, the rotation may be about a central axis of the workpiece as illustrated by arrow **1124**.

[0048] Turning to FIG. **13**, a scanning system **1102** consistent with FIG. **11** is illustrated. Compared to FIG. **11**, the scanning system **1102** of FIG. **13** includes a plurality of insulators **1302-1**, **1302-2**, **1302-3**, . . . **1302**-(*n*−1), and **1302**-*n* that define a plurality of gaps there between **1303-1**, **1303-2**, . . . **1303**-*n*. The scanning system may drive the plurality of insulators **1302-1**, **1302-2**, **1302-3**, . . . **1302**-(*n*−1), and **1302**-*n* relative to the workpiece **138** so the plurality of gaps **1303-1**, **1303-2**, . . . **1303**-*n* pass over the workpiece **138**.

[0049] Accordingly, there is provided an insulating modifier to control a shape of the boundary between the plasma and the plasma sheath. The incident angles of particles that are attracted from the plasma across the plasma sheath may therefore strike an associated workpiece at a large range of incident angles. In one instance, the range of incident angles (θ) may as great as between +60° and −60° centered about 0°. In a plasma doping application, small three dimensional structures on the workpiece may be more uniformly doped. For example, the sidewalls **247** of a trench **244** (see FIG. **2**) may be more uniformly doped compared to a conventional plasma doping apparatus with a much lower range of incident angles.

[0050] 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. Further, 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 plasma processing apparatus comprising:
a process chamber;
a platen positioned in the process chamber for supporting a workpiece;
a source configured to generate a plasma in the process chamber having a plasma sheath adjacent to the front surface of the workpiece; and
an insulating modifier configured to control a shape of a boundary between the plasma and the plasma sheath so a portion of the shape of the boundary is not parallel to a plane defined by a front surface of the workpiece facing the plasma.

2. The plasma processing apparatus of claim **1**, wherein the insulating modifier comprises a pair of insulators defining a gap there between and wherein the shape of the boundary about the gap is a convex shape relative to the plane.

3. The plasma processing apparatus of claim **2**, wherein the pair of insulators comprise a pair of insulting sheets.

4. The plasma processing apparatus of claim **2**, further comprising an actuator mechanically coupled to at least one insulator of the pair of insulators to adjust a horizontal spacing of the gap.

5. The plasma processing apparatus of claim **2**, further comprising an actuator mechanically coupled to the pair of

insulators to adjust a vertical spacing between the pair of insulators and the plane defined by the front surface of the workpiece facing the plasma.

6. The plasma processing apparatus of claim **2**, wherein the pair of insulators are fabricated of quartz.

7. The plasma processing apparatus of claim **2**, further comprising a scanning system configured to move the pair of insulators relative to the workpiece.

8. The plasma processing apparatus of claim **1**, wherein the insulating modifier comprises a plurality of insulators that define a plurality of gaps there between, and wherein the shape of the boundary about each of the plurality of gaps is a convex shape relative to the plane.

9. The plasma processing apparatus of claim **1**, further comprising a bias source configured to bias the workpiece to attract ions from the plasma across the plasma sheath towards the workpiece for doping the workpiece, wherein a range of incident angles of the ions relative to the plane is influenced by the shape of the boundary between the plasma and the plasma sheath.

10. The plasma processing apparatus of claim **9**, wherein the shape of the boundary is a convex shape relative to the plane so the ions attracted from the plasma across the plasma sheath have at least some ion trajectories that cross one another.

11. The plasma processing apparatus of claim **9**, wherein the range of incident angles is between about positive 60° and negative 60° centered about 0°.

12. A method comprising:

positioning a workpiece in a process chamber;

generating a plasma in the process chamber having a plasma sheath adjacent to the front surface of the workpiece; and

modifying a shape of a boundary between the plasma and the plasma sheath with an insulating modifier so a portion of the shape of the boundary is not parallel to a plane defined by a front surface of the workpiece facing the plasma.

13. The method of claim **12**, wherein the modifying operation comprises creating a gap defined by a pair of insulators, and wherein the shape of the boundary about the gap is a convex shape relative to the plane.

14. The method of claim **13**, further comprising adjusting a horizontal spacing of the gap.

15. The method of claim **13**, further comprising adjusting a vertical spacing between the pair of insulators and the plane defined by the front surface of the workpiece facing the plasma.

16. The method of claim **13**, further comprising rotating the workpiece relative to the insulating modifier.

17. The method of claim **12**, wherein a portion of the shape of the boundary between the plasma and the plasma sheath is a convex shape relative to the plane.

18. The method of claim **12**, further comprising attracting ions from the plasma across the plasma sheath towards the workpiece for doping the workpiece, wherein a range of incident angles of the ions relative to the plane is influenced by the shape of the boundary between the plasma and the plasma sheath.

19. The method of claim **18**, wherein the range of incident angles is between about positive 60° and negative 60° centered about 0°.

20. The method of claim **18**, wherein the shape of the boundary between the plasma and the plasma sheath is a convex shape relative to the plane so the ions attracted from the plasma across the plasma sheath have at least some ion trajectories that cross one another.

* * * * *