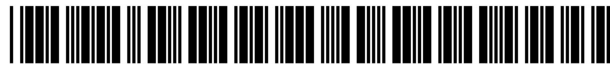
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Godet et al.

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(45) **Date of Patent: Sep. 15, 2015**

(54) **THREE DIMENSIONAL METAL DEPOSITION TECHNIQUE**

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(22) Filed: **Jul. 27, 2012**

(65) **Prior Publication Data**

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(51) **Int. Cl.**

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H01J 37/32	(2006.01)
H01J 37/34	(2006.01)
C23C 14/34	(2006.01)
C23C 14/04	(2006.01)

(52) **U.S. Cl.**

CPC ***H01J 37/32422*** (2013.01); ***C23C 14/046*** (2013.01); ***C23C 14/345*** (2013.01); ***C23C 14/3407*** (2013.01); ***H01J 37/32357*** (2013.01); ***H01J 37/32403*** (2013.01); ***H01J 37/32623*** (2013.01); ***H01J 37/32633*** (2013.01); ***H01J 37/32642*** (2013.01); ***H01J 37/3414*** (2013.01); ***H01J 37/3417*** (2013.01); ***H01J 37/3467*** (2013.01); *H01J 2237/08* (2013.01); *H01J 2237/31701* (2013.01)

(58) **Field of Classification Search**

CPC combination set(s) only.
See application file for complete search history.

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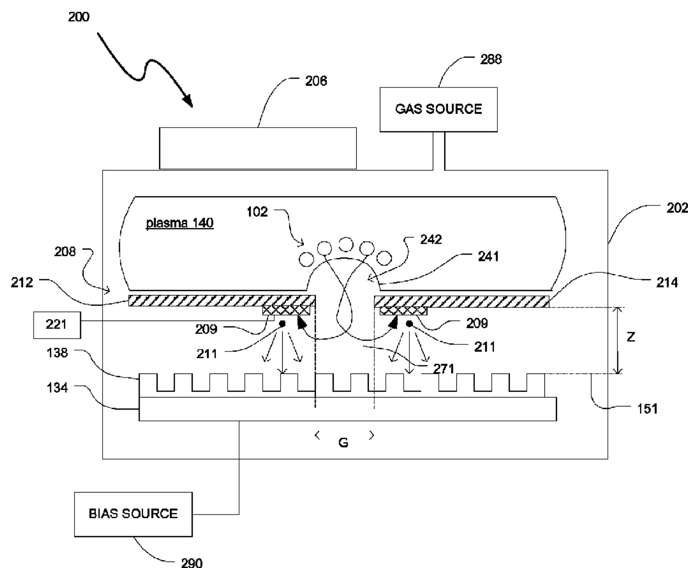
(57) **ABSTRACT**

A plasma processing apparatus is disclosed. The plasma processing apparatus includes a source configured to generate a plasma in a process chamber having a plasma sheath adjacent to the front surface of a workpiece, and a plasma sheath modifier. The plasma sheath modifier controls 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. A metal target is affixed to the back surface of the plasma sheath modifier so as to be electrically insulated from the plasma sheath modifier and is electrically biased such that ions exiting the plasma and passing through an aperture in the plasma sheath modifier are attracted toward the metal target. These ions cause sputtering of the metal target, allowing three dimensional metal deposition of the workpiece.

20 Claims, 7 Drawing Sheets



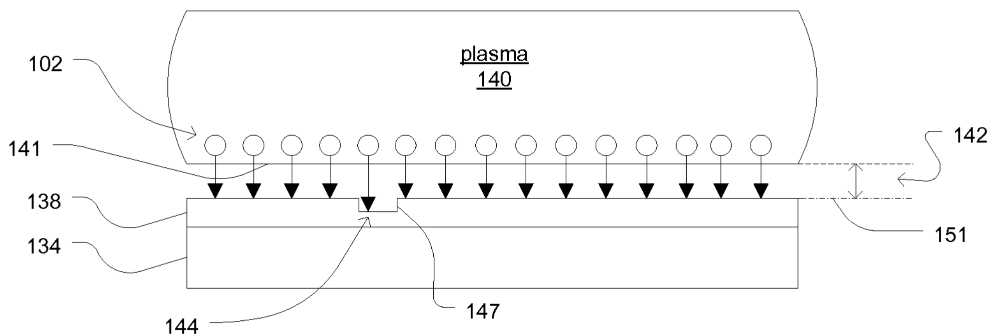


FIG. 1
Prior Art

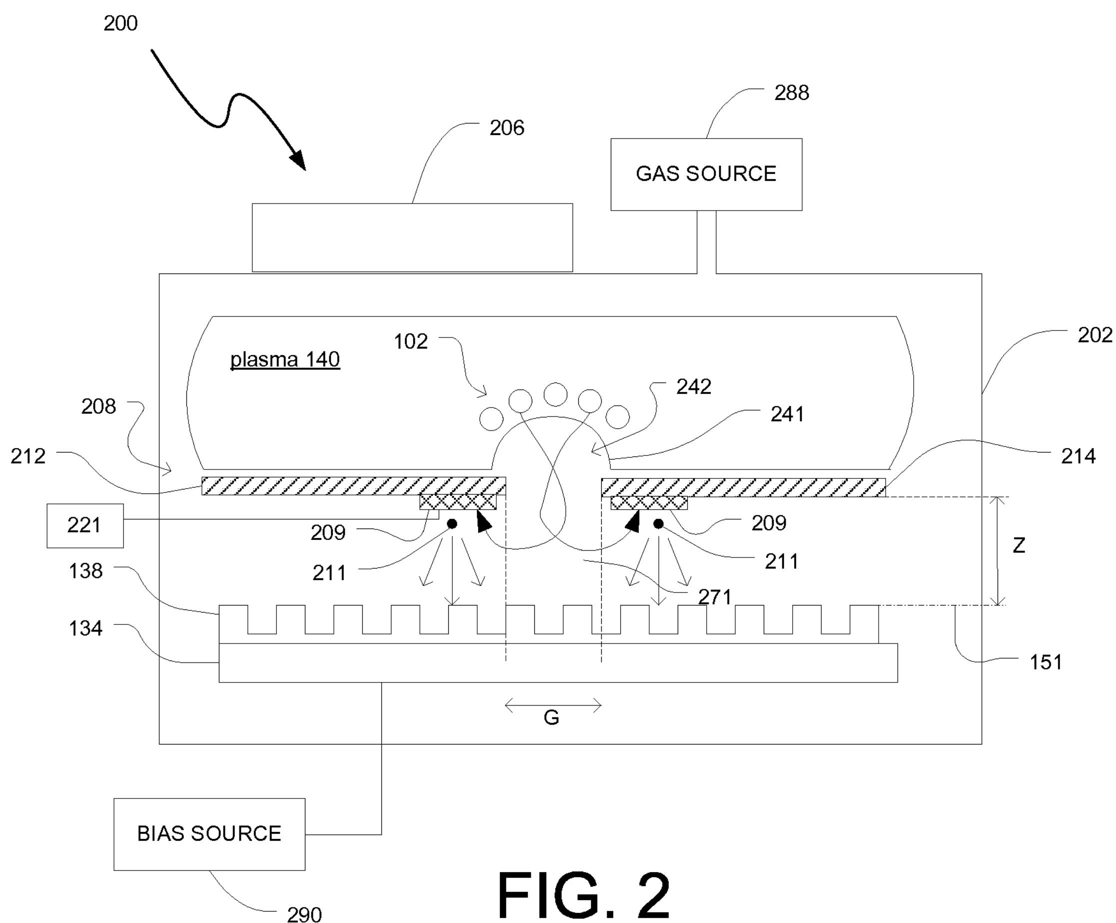


FIG. 2

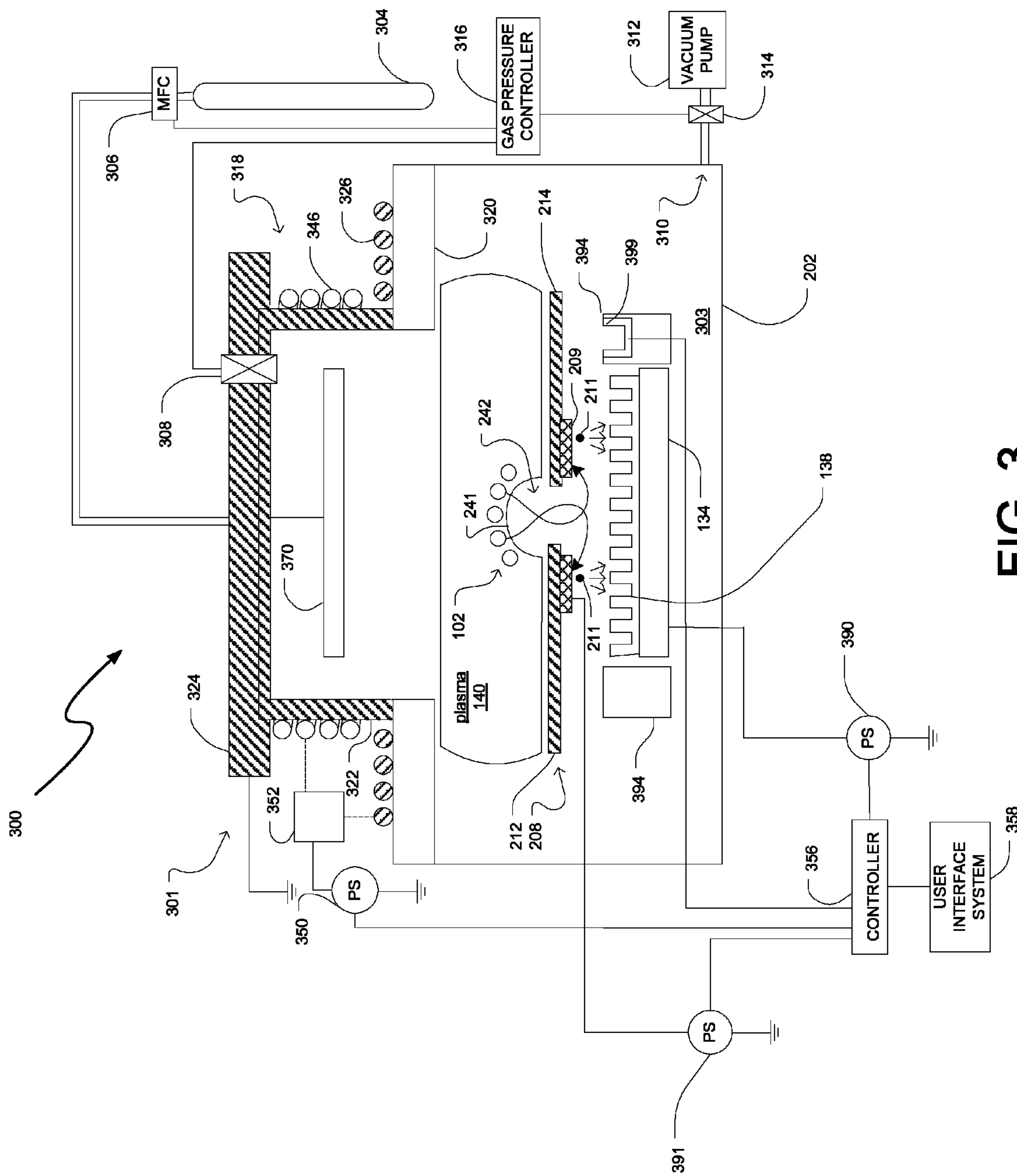


FIG. 3

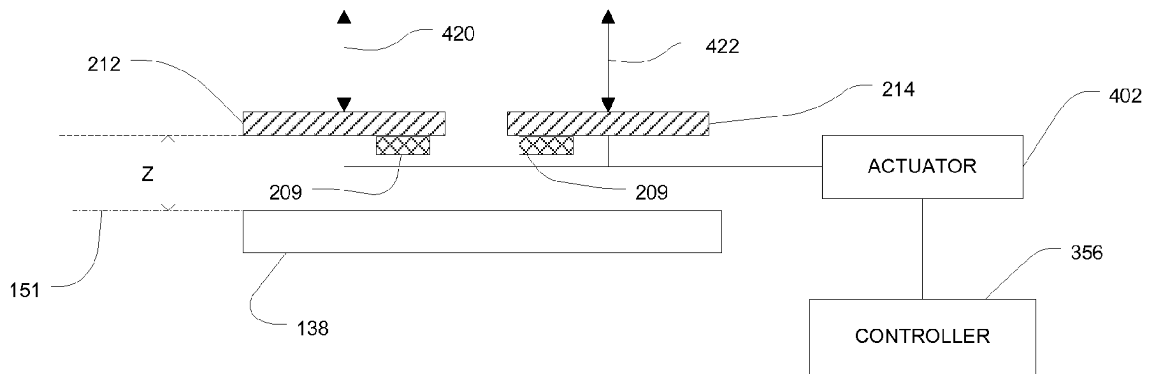


FIG. 4

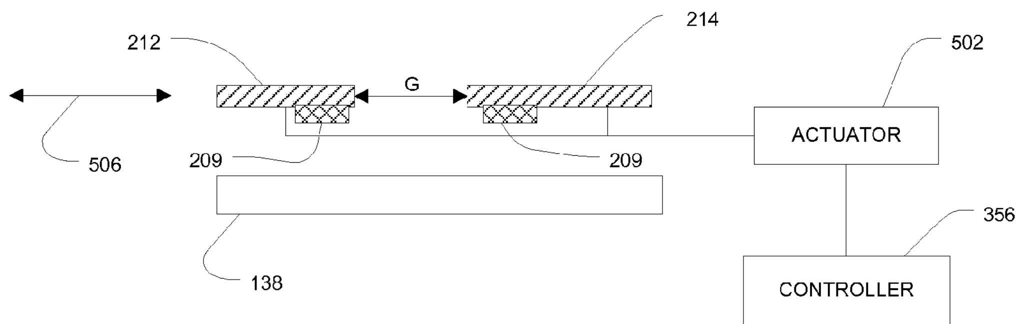


FIG. 5

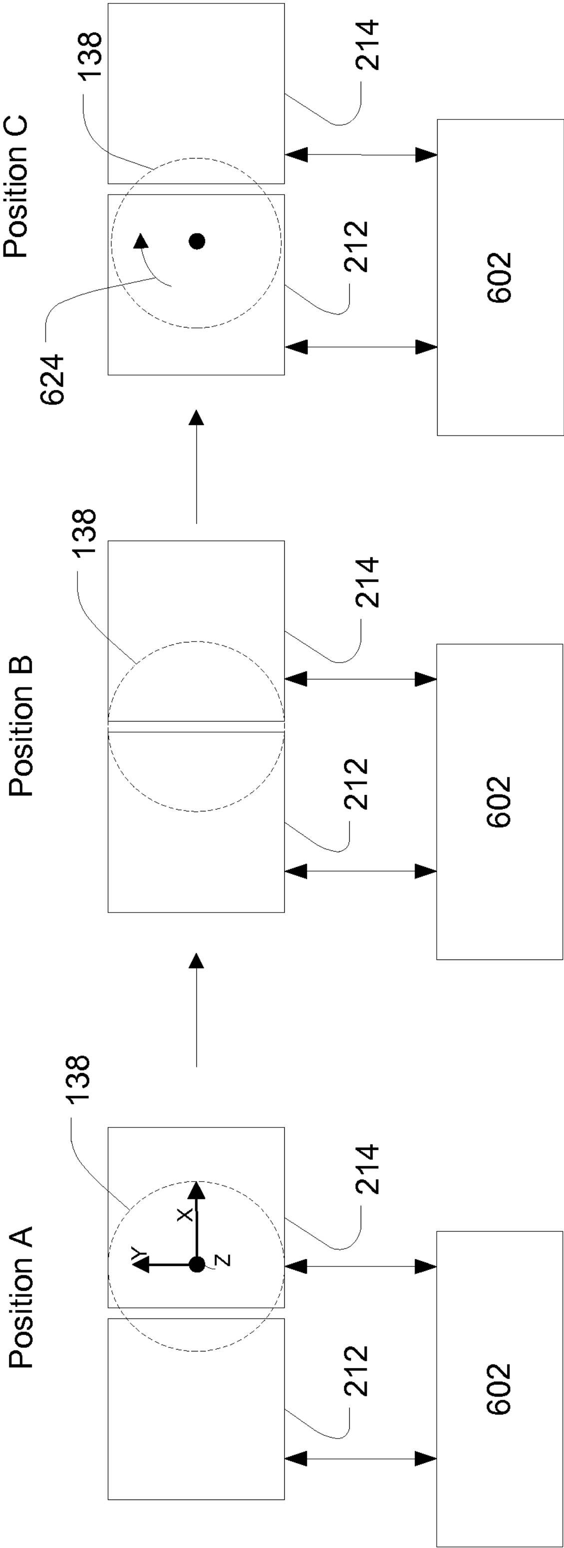


FIG. 6

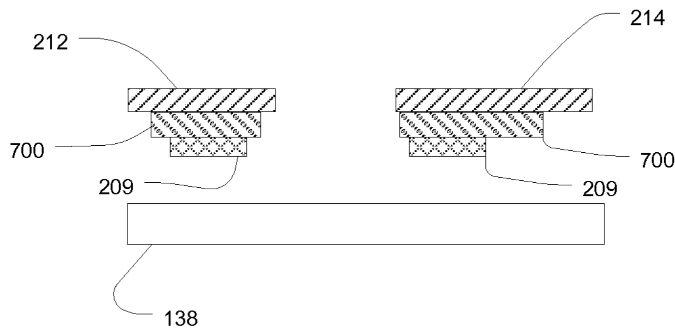


FIG. 7

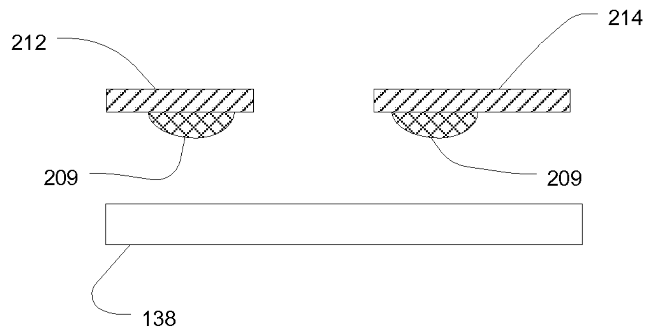


FIG. 8A

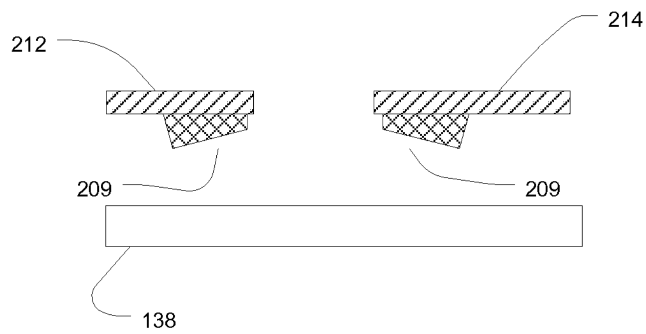


FIG. 8B

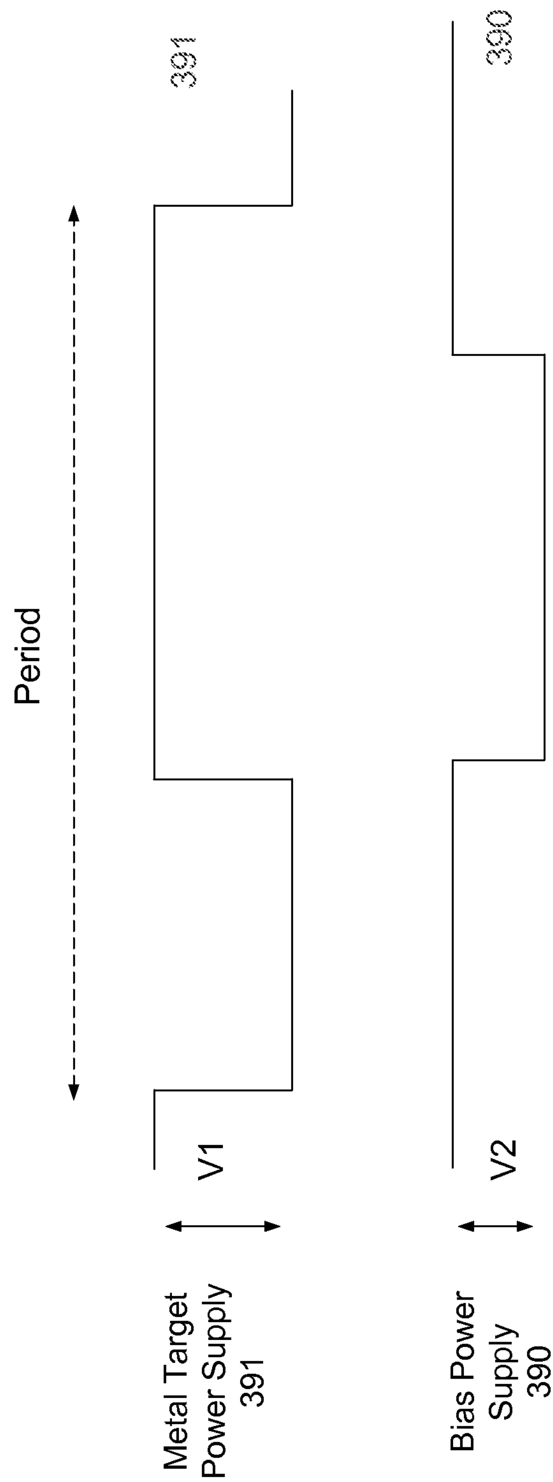


FIG. 9

910
920
930
980
Z
985
138
942
951
G
Plasma 940
209
952
931
921
950
T
Power Supply 990
Metal Target Power Supply 391
Bias Power Supply 390

FIG. 10

THREE DIMENSIONAL METAL DEPOSITION TECHNIQUE

FIELD

This disclosure relates to plasma processing, and more particularly to a plasma processing apparatus for metal deposition.

BACKGROUND

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.

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."

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°.

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**.

In addition, this system can be used for deposition of dopants, such as phosphorus, however, it is ineffective for metal deposition. Accordingly, there is a need for a plasma processing apparatus which overcomes the above-described inadequacies and shortcomings.

SUMMARY

A plasma processing apparatus and method are disclosed. The plasma processing apparatus includes a process chamber, a platen 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 a plasma sheath modifier. The plasma sheath 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. A metal target is affixed to the back surface of the plasma sheath modifier so as to be electrically insulated from the plasma sheath modifier and is electrically biased such that ions exiting the plasma and passing through an aperture in the plasma sheath modifier are attracted toward the metal target. These ions cause sputtering of the metal target, allowing three dimensional metal deposition of the workpiece.

BRIEF DESCRIPTION OF THE DRAWINGS

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:

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

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

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

FIG. **4** is a block diagram of a system to control a vertical spacing between a pair of modifiers and a workpiece;

FIG. **5** is a block diagram of a system to control a horizontal spacing between a pair of modifiers;

FIG. **6** shows relative movement between the modifier sheets and a disk shaped workpiece;

FIG. **7** shows a block diagram of the plasma sheath modifier and metal target according to another embodiment;

FIGS. **8**A-**8**B show alternate shapes of the metal target according to other embodiments;

FIG. **9** shows a representative timing diagram; and

FIG. **10** is a block diagram of a plasma doping apparatus consistent with an embodiment of the disclosure.

DETAILED DESCRIPTION

FIG. **2** is a block diagram of one plasma processing apparatus **200** having a plasma sheath modifier **208** and a metal target **209** electrically insulated from the plasma sheath modifier consistent with an embodiment of the disclosure. The plasma sheath 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**. The plasma sheath modifier **208** may be an insulator, a conductor, or a semiconductor material. If the plasma sheath modifier **208** is an insulating material, the metal target **209** may be affixed directly to the plasma sheath modifier **208**, as seen in FIG. **2**. In other embodiments, the plasma sheath modifier **208** may be a semiconducting or conducting material. In this case, the metal target **209** may be affixed to the plasma sheath modifier **208** and be electrically isolated from the plasma sheath modifier **208**, such as by a layer of insulating material **700** interposed between the metal target **209** and the plasma sheath modifier **208**, as shown in FIG. **7**. Thus, the term "affixed" referred to direct contact between the metal target **209** and the plasma sheath modifier **209**, or indirect contact where a layer of insulating material **700** is disposed between the plasma sheath modifier **208** and the metal target **209**.

Returning to FIG. **2**, the metal target **209** may be electrically biased. Accordingly, ions **102** that are attracted from the plasma **140** across the plasma sheath **242** may strike the metal target **209** at a specific range of incident angles. These ions striking the metal target **209** cause the target to sputter, thereby depositing the metal particles **211** at a wide range of incident angles.

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.

The plasma processing apparatus **200** may include a process chamber **202**, a platen **134**, a source **206**, and the plasma sheath modifier **208**. The platen **134** is positioned in the process chamber **202** for supporting the workpiece **138**. The workpiece **138** 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 or 450 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 plasma sheath modifier **208** may be made of an insulating material and includes a pair of modifiers **212** and **214** defining a gap there between having a horizontal spacing (G). In other embodiments, the plasma sheath modifier **208** may include only one modifier having an aperture. As stated above, in other embodiments, the plasma sheath modifier **208** may be a semiconducting or conducting material. Although FIG. **2** illustrates a plasma sheath modifier **208** that is an insulator where the metal target **209** is attached directly to the modifiers **212** and **214**, it is understood that the disclosure is not limited to only insulating plasma sheath modifiers **208**. FIG. **7** illustrates a mechanism by which a metal target **209** may be used with a semiconducting or conducting plasma sheath modifier **208**.

The pair of modifiers **212** and **214** may be a pair of sheets having a thin, flat shape. In other embodiments, the pair of modifiers **212** and **214** may be other shapes such as tube shaped, wedge shaped, and/or have a beveled edge proximate the gap.

In one embodiment, the horizontal spacing of the gap defined by the pair of modifiers **212** and **214** may be about 6.0 millimeters (mm). The pair of modifiers **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.

A metal target **209** is affixed on the back surface of the modifiers **212** and **214**, in proximity to the gap. If the modifiers **212** and **214** are insulators, the metal target **209** may be deposited directly on the modifiers **212** and **214**. Alternatively, the metal target **209** may be bonded, applied as a coating or mechanically attached. The metal target **209** may vary in thickness from a few microns to several millimeters. The thickness of the target **209** may determine its useful life. If the modifiers **212** and **214** are semiconducting or conducting material, an insulating layer **700** is disposed on the modifiers **212** and **214** as seen in FIG. **7**. The metal target **209** is then applied to the insulating material **700** using any of the methods described above.

The metal target **209** may be any suitable metal of compound semiconductor, including but not limited to Cu, Al, W, Ti, Hf, Ta, Co, Pd, Pt, Ru, Zn, ZnTe, and CuTe, and may be selected based on the required deposition layer composition. The metal target **209** may be textured to control the sputtering process efficiency. These textures include pyramid, porous, wave or any suitable shape.

In some embodiments, the metal target **209** is disposed about the entire perimeter of the gap or aperture. In other embodiments, the metal target **209** is disposed about only part of the perimeter or aperture. The metal target **209** may be electrically biased using a power supply **221** so as to attract ions **102** passing through the gap. These ions **102** strike the metal target **209**, causing it to sputter. These sputtered metal particles **211** are then attracted toward the platen **134**, and deposited at a wide range of angles on the workpiece **138**. These metal particles **211** may be ions or may be neutrals.

While FIG. **2** shows the metal target **209** as a flat piece of metal, the disclosure is not limited to this shape. For example, the shape of the metal target **209** may be optimized for improved sputtering yield. For example, the metal target **209** may be a curved, angled, or curvilinear shape, such as is shown in FIGS. **8**A-B. Thus, shapes which are non-linear or curved may be used. In addition, the shape of the metal target **209** may be such that the surface of the metal target closest to the workpiece **138** is not parallel to the front surface of the workpiece.

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. HCl, Cl_2, chlorine based molecules and other compounds that cause a chemical reaction with the metal target **209** in addition to the sputtering effect may also be used. Additionally, mixtures of gasses including N_2, He, H_2 and Ar may be used. The source **206** may generate the plasma **140** by exciting and ionizing the gas provided to the process chamber **202**. Ions **102** may be attracted from the plasma **140** across the plasma sheath **242** by different mechanisms. In the embodiment of FIG. **2**, the bias source **221** is configured to negatively bias the metal target **138** to attract ions **102** from the plasma **140** across the plasma sheath **242**. The bias source **221** may be a DC power supply to provide a DC voltage bias signal or an RF power supply to provide an RF bias signal. Furthermore, the bias source **221** may be a constant voltage output or may be pulsed. This operation may be carried out at room temperature of at an elevated temperature, as desired.

Advantageously, the plasma sheath modifier **208** modifies the electric field 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 plasma sheath modifier **208** includes a pair of modifiers **212** and **214**, which are insulators and may be fabricated of quartz, alumina, boron nitride, glass, silicon nitride, etc. In other embodiments, such as FIG. **7**, semiconducting or conducting material may be used for the modifiers **212** and **214**. In these embodiments, the semiconductor materials may be fabricated of silicon, doped silicon, silicon carbide and other suitable materials.

Returning to FIG. **2**, 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 **221** biases the metal target **209**, ions **102** are attracted across the plasma sheath **242** through the gap between the modifiers **212** and **214** at a predetermined range of incident angles. Depending on a number of factors including, but not limited to, the horizontal spacing (G) between the modifiers **212** and **214**, the vertical spacing (Z) of the modifiers above the plane **151**, the dielectric constant of the modifiers **212** and **214**, the voltage of the bias source **221**, and other plasma process

parameters, the ions **102** may strike the metal target **209** at a predetermined range of incident angles.

The ions **102** striking the metal target **209** cause metal particles **211** to sputter from the metal target **209**. Hence, the angle at which the ions **102** strike the metal target **209** may determine the angle at which the metal particles **211** sputter toward the workpiece **138**. By varying the angle at which the ions **102** strike the metal target **209**, small three dimensional structures on the workpiece **138** may be treated uniformly by the metal ions **102**. In addition, by varying the angle at which the ions **102** strike the metal target **209**, the sputtering rate may also be controlled.

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 modifiers **212** and **214** to control a shape of the boundary **241** between the plasma **140** and the plasma sheath **242**.

The pair of modifiers **212** and **214** defines a gap or aperture therebetween. One or more metal targets **209** are disposed proximate to the gap or aperture. The one or more metal targets **209** may be electrically coupled to metal target power supply **391**. Metal target power supply **391** may provide a constant voltage or a pulsed voltage, as desired.

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**.

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**.

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.

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.

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**.

In one embodiment, the metal target power supply **391** is negatively biased, and the bias power supply **390** is maintained at ground potential. The ions **102** from the plasma **140** are accelerated toward the metal target **209**. By varying the gap width, the relative vertical positions of the modifiers **212** and **214**, the vertical distance between the modifiers **212** and **214** and the workpiece **138**, and the voltage of metal target power supply **391**, the incident angle of the ions **102** exiting the plasma **140** can be tuned. These ions **102** strike the metal targets **209** and cause it to sputter and generate metal particles **211** which are emitted toward the workpiece **138** at a wide range of angles. These metal particles **211** are then deposited or implanted in the three dimensional structures of the workpiece **138**. The metal target **209** may be biased at a voltage between −100V and −20 kV. In some embodiments, the bias applied to the metal target **209** may vary during the sputtering process. For example, the bias voltage may initially be −0.5 kV which creates sputtered metal particles **211** having a certain energy. As the workpiece **138** is coated, the bias voltage may approach −2 kV, causing metal particles **211** in subsequent passes to be projected toward the workpiece **138** with increasing energy.

By optimizing the angular distribution of ions **102**, the trajectories of the metal particles **211** can be optimized to obtain adequate sidewall coverage. Furthermore, the sputtering yield is dependent on the incident ion angle and metal target temperature. For example a 60° incident angle may have three times the sputtering yield of a 10° incident angle. By utilizing multiple incident angles in parallel, for example, from 0° to 60°, a variety of sputtered metal particles **211** with multiple angles may be generated.

In another embodiment, the bias power supply **390** may be negatively biased. This negative bias may be less negative than the voltage applied to the metal targets **209**, so that the ions **102** are more attracted to the metal targets **209**. For example, in one embodiment, the metal target **209** may be biased at −2 kV, while the workpiece **138** is biased at −1 kV. In this case, the ions **102** exiting the plasma **140** are accelerated toward the workpiece **138** and the metal target **209** at the same time. Therefore, in addition to the parameters listed above, the interaction between the ions **102** and the electrical

fields created by the metal targets **209** and the workpiece **138** will affect the angles at which the ions **102** strike the metal targets **209**.

In another embodiment, the metal target power supply **391** and the bias power supply **390** may provide time varying outputs, such as pulses. These pulses can be synchronized or coordinated to produce the desire behavior. For example, in one embodiment, the metal target power supply **391** and the bias power supply **390** may create negative voltage pulses simultaneously. In other embodiments, one of the power supplies provides a pulsed voltage output. Sometime after the start of this pulsed voltage output, the other power supply provides a pulsed voltage output. In some embodiments, the second power supply may output the pulsed output at the end of the first pulsed output. FIG. **9** shows a representative timing diagram showing the relationship between the metal target power supply **391** and the bias power supply **390**. In one embodiment, the metal target power supply **391** generates pulses at a pulse frequency of about 5 kHz and each pulse has a duration of between 25 to 100 us. The bias power supply **390** also generates pulses having a duration of between 25 to 100 us. In FIG. **9**, these pulses are coordinated such that the bias voltage pulse follows the metal target pulse. Thus, ions **102** are attracted first to the metal target **209**. As metal particles **211** are sputtered, the bias voltage is pulsed, drawing those metal particles **211** toward the workpiece **138**. In another embodiment, the metal target bias could be continuous DC voltage, while the bias voltage is pulsed.

The frequency of the pulsed platen signal and/or the duty cycle of the pulses may be selected to provide a desired sputter rate. The amplitude of the pulsed platen signal may be selected to provide a desired energy.

In some embodiments, such as shown in FIG. **4**, the vertical spacing (Z) between plasma sheath modifier and the plane **151** defined by the front surface of the workpiece **138** may be adjusted. An actuator **402** may be mechanically coupled to the pair of modifiers **212** and **214** to drive the modifiers **212** and **214** in a vertical direction, as indicated by lines **420** and **422**, respectively, relative to the plane **151**. The Z position of the pair of modifiers **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** or metal targets **209**. This actuator **402** may be controlled by a controller, such as controller **356**.

Turning to FIG. **5**, a block diagram of another embodiment consistent with the present disclosure is illustrated where the horizontal spacing (G) between modifiers **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 FIG. **4**. An actuator **502** may be mechanically coupled to at least one of the pair of modifiers **212** and **214** to drive the modifiers in the direction shown by the arrow **506** relative to one another. The actuator **502** may be controlled by a controller such as controller **356**.

As shown in FIG. **6**, in some embodiments, the plasma processing apparatus **200** may have a scanning system **602** to drive a plasma sheath modifier relative the workpiece **138**. The scanning system **602** may include an actuator mechanically coupled to the modifiers **212** and **214** to drive the same. This actuator (not shown) may be controlled by a controller, such as controller **356** (See FIG. **3**). In the embodiment of FIG. **6**, the scanning system **602** may drive the modifiers **212** and **214** 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 modifiers **212** and **214**. If a Cartesian coordinate system is defined as detailed in FIG. **6**, the modifiers **212** and **214** are driven in the X direction of FIG. **6**. In other embodiments, the modifiers **212** and **214** or another set of different modifiers 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 **602** drives the modifiers **212** and **214** in one direction. The workpiece **138** may also be rotated by a predetermined rotation angle after the scanning system **602** drives the modifiers **212** and **214** in one direction. In one example, the rotation may be about a central axis of the workpiece as illustrated by arrow **624**.

FIG. **10** shows another embodiment of ion implanter that may be used in accordance with an embodiment. The ion source **910** includes a chamber **921** having sidewalls **920** and an open end **930**. Plasma **940** is generated within the chamber **921**. Plasma can be generated using any suitable means, including indirectly heated cathode (IHC), RF energy or other means. In the chamber **921**, disposed near the open end **930** are one or more plasma sheath modifiers **950**. The plasma sheath modifiers **950** are configured to have an extraction aperture **931**. The plasma sheath modifiers **950** are used to control a shape of the boundary **942** between the plasma **940** and the plasma sheath proximate the extraction aperture **931** when ions are extracted from the chamber **921** of the ion source **910**. The plasma sheath modifier **950** may include a pair of modifiers **951**, **952** defining a gap there between. Other embodiments may have multiple pairs of modifiers defining multiple gaps.

The modifiers **951**, **952** may be fabricated of semiconductor materials, including, but not limited to, silicon, germanium, silicon carbide, silicon germanium, aluminum antimonide, aluminum nitride, and gallium arsenide. The modifiers **951**, **952** may also be fabricated of doped semiconductor materials including, for example, doped silicon and doped silicon carbide. To form the doped silicon carbide, silicon carbide may be doped with species such as nitrogen, boron, and aluminum to name only several dopants.

The pair of modifiers **951**, **952** may also be a pair of sheets having a thin, flat shape. The pair of modifiers **951**, **952** defines a gap there between having spacing (G). The pair of semiconductors **951**, **952** may also be positioned a vertical spacing (Z) above the workpiece **138**.

Depending on a number of factors including, but not limited to, the horizontal spacing (G) between the pair of modifiers **951**, **952**, the vertical spacing (Z) of the modifiers above the workpiece **138**, a difference in vertical spacing between each modifier **951**, **952** above the workpiece **138**, the modifiers material including its relative conductivity, the thickness (T) of the modifiers **951**, **952**, the temperature of the pair of modifiers **951**, **952**, and other process parameters of the ion source, the shape of the boundary **942** can be controlled.

Metal targets **209** are disposed proximate the side of the modifiers **951**, **952** closest to the workpiece **138**. As described above, the metal targets **209** may be biased by metal target power supply **391**.

The ion source **910** may be a component of an ion implanter having an end station **980** positioned downstream of the extraction aperture **931** of the ion source **910**. The end station **980** may be positioned in close proximity (e.g., in one embodiment less than 12 inches) to the extraction aperture **931** of the ion source **910** thereby creating a relatively short distance for the particles to travel. The end station **980** may include a platen **985** to support a workpiece **138**. The platen **985** may be an electrostatic platen to secure the workpiece **138** with electrostatic forces as is known in the art. The workpiece **138** may include, but not be limited to, a solar cell, flat panel, magnetic media, semiconductor wafer, etc.

In some embodiments, the metal targets **209** may be biased by a metal target power supply **391** to create forces to extract the ions from the extraction aperture **931** toward the metal targets **209**. The workpiece **138** may also be biased by a bias power supply **390**. The bias signal to the workpiece **138** may be a pulsed bias signal having ON and OFF time interval so that particles are attracted during the ON intervals but not the OFF intervals. Similarly, the bias signal to the metal targets **209** may be a pulsed bias signal. One reason for a pulsed bias signal is to control the amount of charge accumulation on the workpiece **138** to acceptable levels during ion treatment, while trying to balance charge control with throughput requirements for an associated ion implanter. In this embodiment, the interaction between metal target power supply **391** and bias power supply **390** may be as described in FIG. **9**.

In another embodiment, a power supply **990** is used to bias the sidewalls **920** of the ion source **910**. The workpiece **138** may also be biased, such as by a bias power supply **390**, and the metal targets **209** may be biased by a metal target power supply **391**. In this embodiment, the sidewalls **920** of the ion source may be positively biased, such as at about 2 kV. In this embodiment, the metal targets **209** may be grounded, so as to attract positive ions from within the chamber **921** toward the metal targets **209**. The workpiece **138** may be less negatively biased than the metal targets **209**, such as at 1 kV, so that ions are primarily attracted to the metal targets **209**. As described above, the power supplies, such as power supply **990**, metal target power supply **391** and bias power supply **390** may be pulsed and synchronized with each other to optimize the deposition of particles on the workpiece **138**.

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 proximate a front surface of the workpiece;

an insulating plasma sheath modifier, having a gap, disposed between the plasma and the platen, such that a first surface of the insulating plasma sheath modifier is proximate the plasma and a second surface is closer to the platen, and 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; and

a metal target, affixed to the second surface of the insulating plasma sheath modifier closer to the platen,

wherein ions in the plasma are attracted across the boundary through the gap and strike the metal target at a plurality of incident angles.

2. The plasma processing apparatus of claim **1**, further comprising a power supply configured to bias the metal target to attract ions from the plasma across the plasma sheath toward the metal target so as to cause metal particles to sputter from the metal target.

3. The plasma processing apparatus of claim **2**, further comprising a bias source configured to bias the workpiece to attract the metal particles towards the workpiece for depositing metal on the workpiece, wherein a range of incident angles of the metal particles relative to the plane is influenced by the shape of the boundary between the plasma and the plasma sheath.

4. The plasma processing apparatus of claim **3**, wherein the workpiece is less negatively biased than the metal target.

5. The plasma processing apparatus of claim **2**, wherein the power supply supplies a pulsed bias signal to the metal target.

6. The plasma processing apparatus of claim **3**, wherein the bias source supplies a pulsed bias signal to the workpiece.

7. The plasma processing apparatus of claim **3**, wherein the power supply supplies a first pulsed bias signal to the metal target and the bias source supplies a second pulsed bias signal to the workpiece, wherein the first pulsed bias signal and the second pulsed bias signal are coordinated to optimize sputtering of metal particles onto the workpiece.

8. The plasma processing apparatus of claim **1**, wherein the metal target is shaped such that a surface of the metal target closest to the workpiece is not parallel to the front surface of the workpiece.

9. A sputtering system, comprising:

a chamber having sidewalls and an open end, and configured to generate a plasma having a plasma sheath;

an insulating plasma sheath modifier disposed near the open end of the chamber, such that a first surface of the insulating plasma sheath modifier is proximate the plasma and a second surface is distal from the chamber, the insulating plasma sheath modifier configured to have an extraction aperture and 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; and

a metal target affixed to the second surface of the insulating plasma sheath modifier distal from the chamber,

wherein ions in the plasma are attracted across the boundary through the extraction aperture and strike the metal target at a plurality of incident angles.

10. The sputtering system of claim **9**, further comprising a platen, configured to hold a workpiece, the platen located such that the metal target is disposed between the chamber and the platen.

11. The sputtering system of claim **10**, comprising a bias supply configured to bias the workpiece to attract metal particles from the metal target towards the workpiece for depositing metal on the workpiece, wherein a range of incident angles of the metal particles relative to the workpiece is influenced by the shape of the boundary between the plasma and the plasma sheath.

12. The sputtering system of claim **11**, further comprising a power supply to positively bias the sidewalls relative to the metal target.

13. The sputtering system of claim **12**, wherein the workpiece is more positively biased than the metal target.

14. The sputtering system of claim **12**, wherein the power supply supplies a pulsed bias signal to the sidewalls.

15. The sputtering system of claim **14**, wherein the bias supply supplies a second pulsed bias signal to the workpiece, and the pulsed bias signal and the second pulsed bias signal are coordinated so as to optimize sputtering of metal particles on the workpiece.

16. The sputtering system of claim **11**, comprising a power supply configured to negatively bias the metal target relative to the sidewalls so as to attract ions from the plasma across the plasma sheath toward the metal target so as to cause the metal particles to sputter from the metal target.

17. The sputtering system of claim **16**, wherein the workpiece is more positively biased than the metal target.

18. The sputtering system of claim **16**, wherein the power supply supplies a pulsed bias signal to the metal target.

19. The sputtering system of claim **18**, wherein the bias supply supplies a second pulsed bias signal to the workpiece, and the pulsed bias signal and the second pulsed bias signal are coordinated so as to optimize sputtering of metal particles on the workpiece.

20. The sputtering system of claim **9**, wherein the metal target is shaped such that a surface of the metal target closest to the workpiece is not parallel to the front surface of the workpiece.

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