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(54) **PLASMA PROCESSING METHODS USING MULTIPHASE MULTIFREQUENCY BIAS PULSES**

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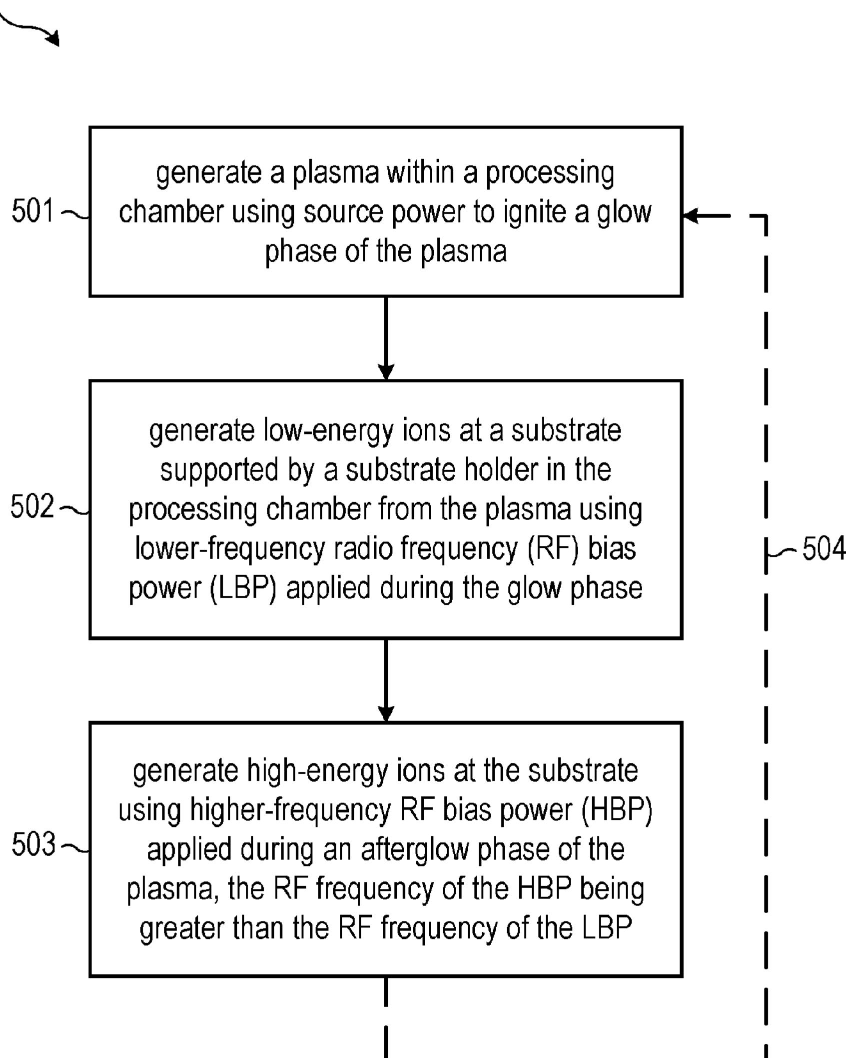
(57) **ABSTRACT**

A plasma processing method includes generating a plasma within a processing chamber using source power to ignite a glow phase of the plasma, generating low-energy ions at a substrate supported by a substrate holder in the processing chamber from the plasma using lower-frequency radio frequency bias power applied during the glow phase, and generating high-energy ions at the substrate using higher-frequency radio frequency bias power applied during an afterglow phase of the plasma. The frequency of the higher-frequency radio frequency bias power is greater than the frequency of the lower-frequency radio frequency bias power.



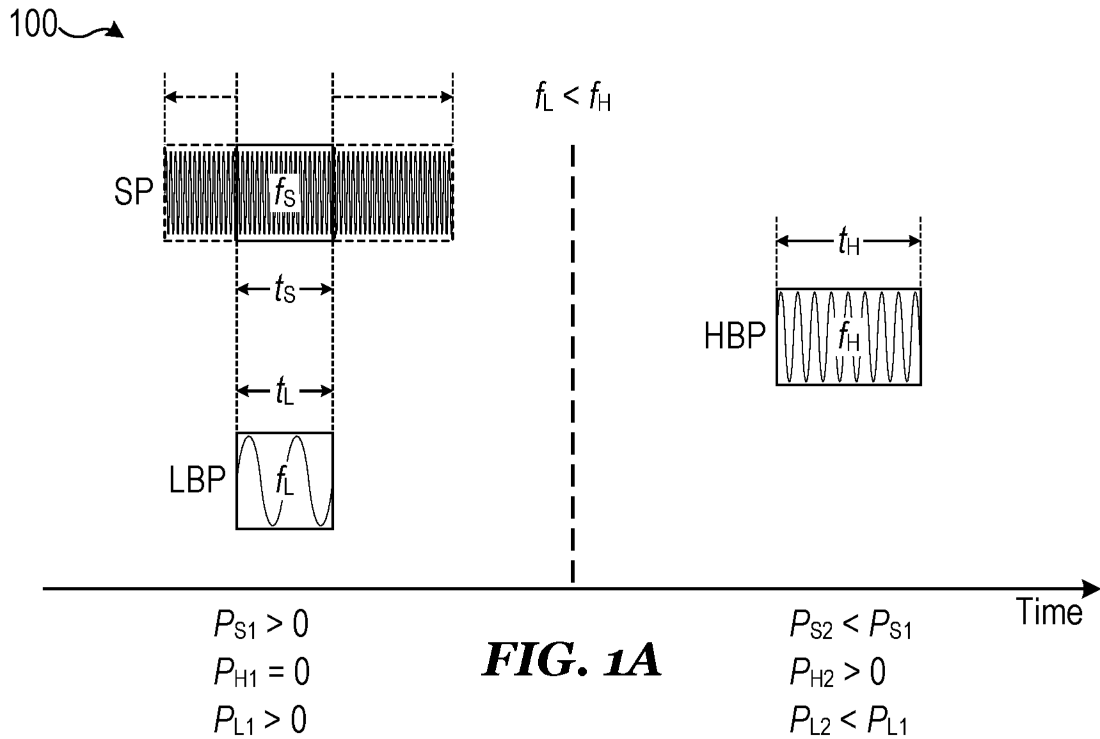


FIG. 1A

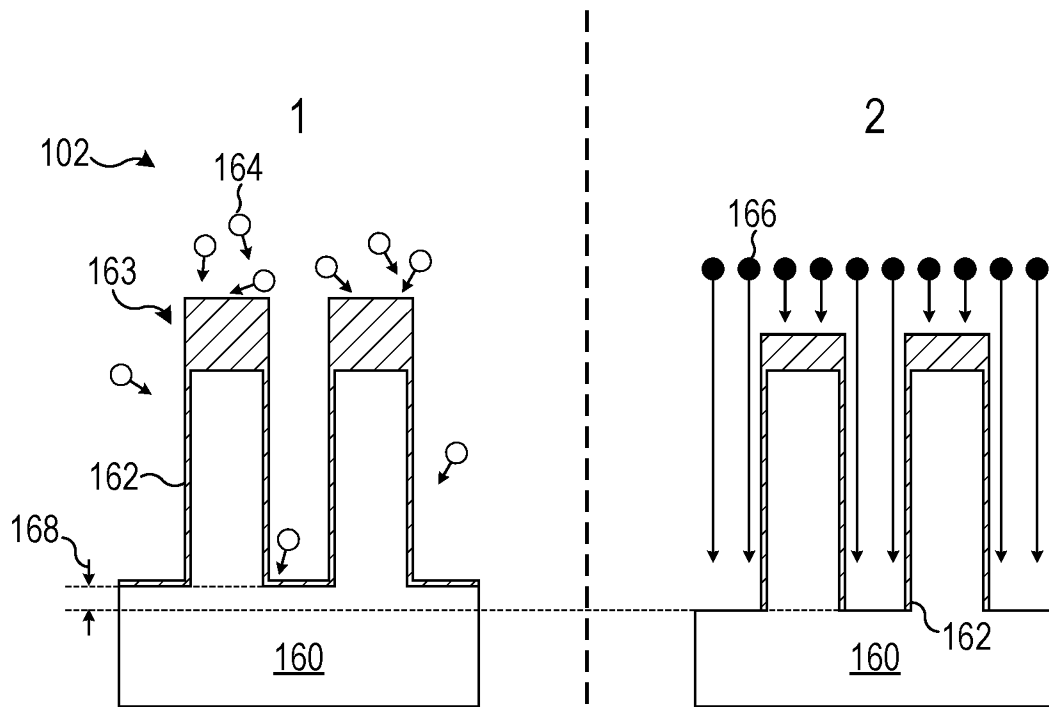


FIG. 1B

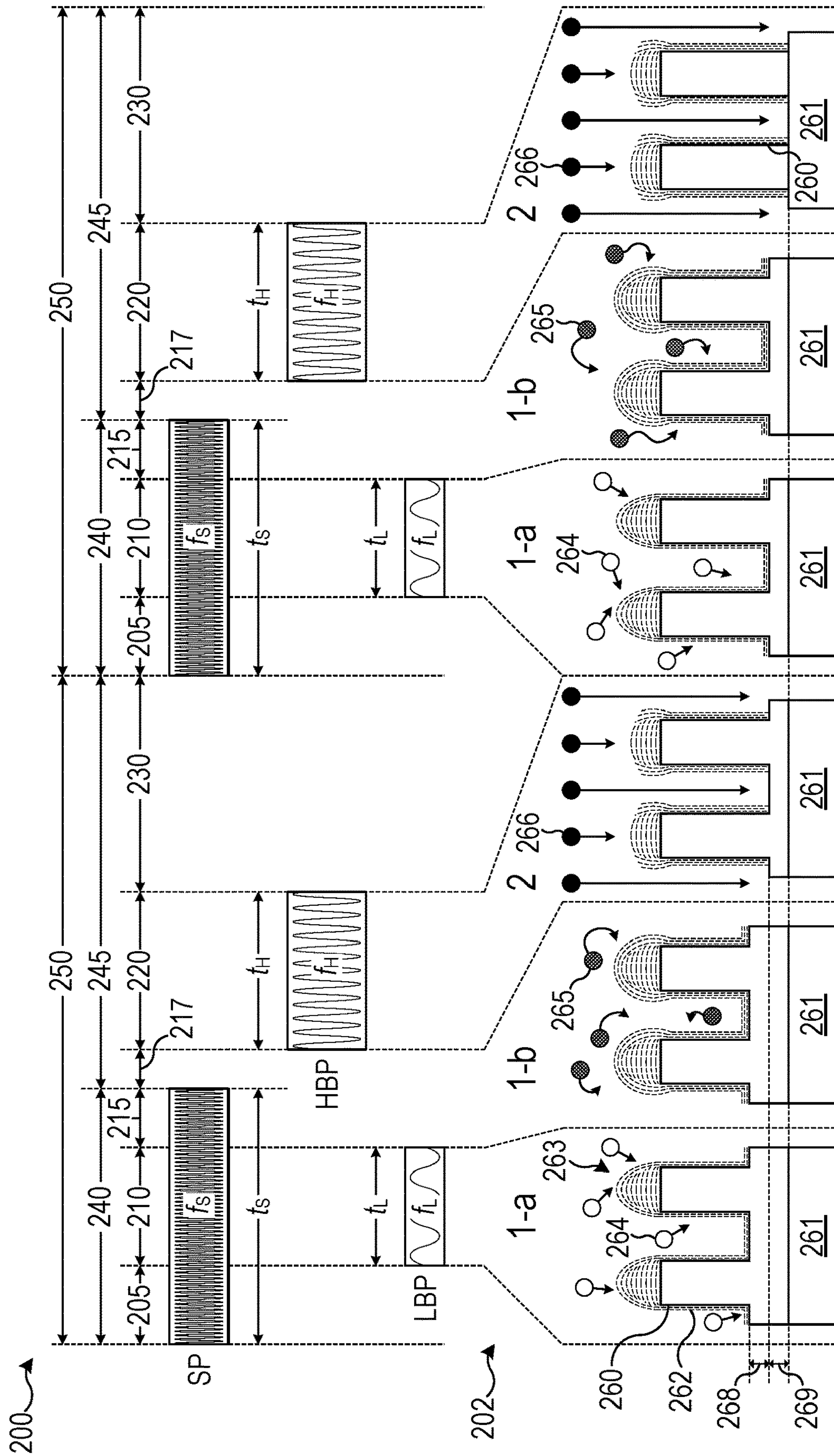


FIG. 2

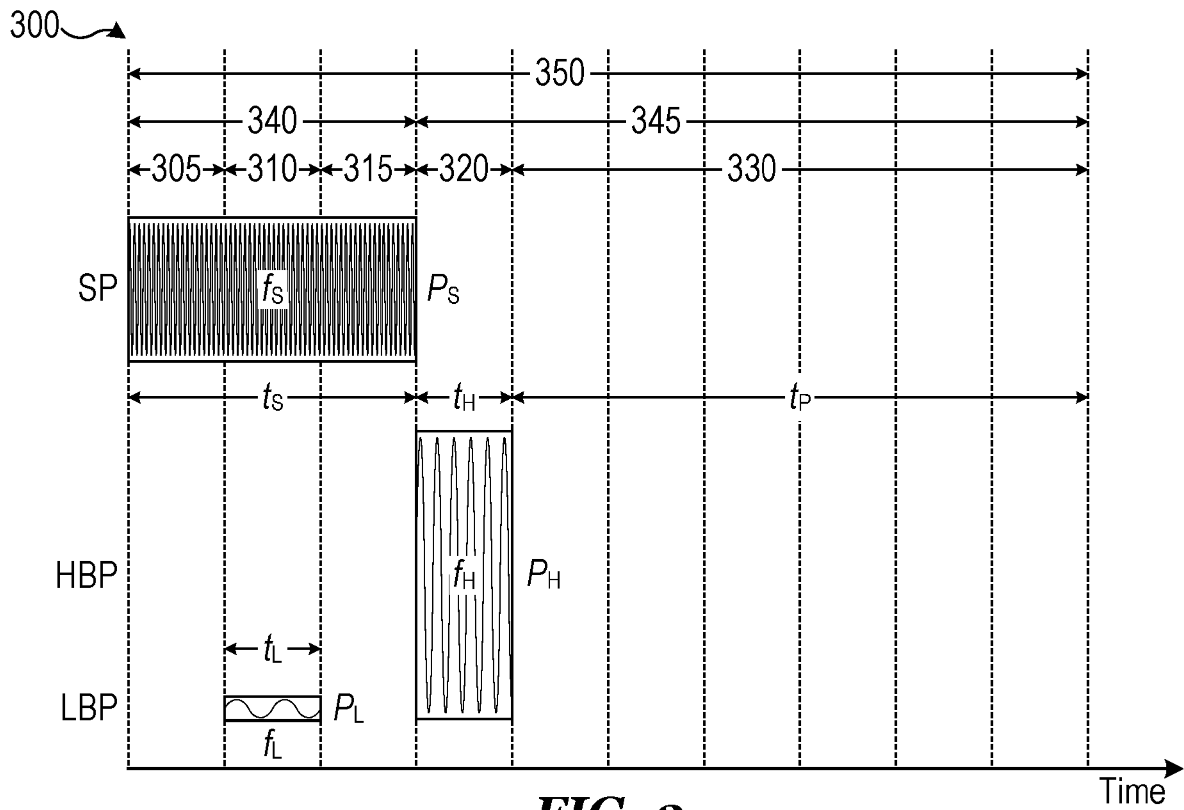


FIG. 3

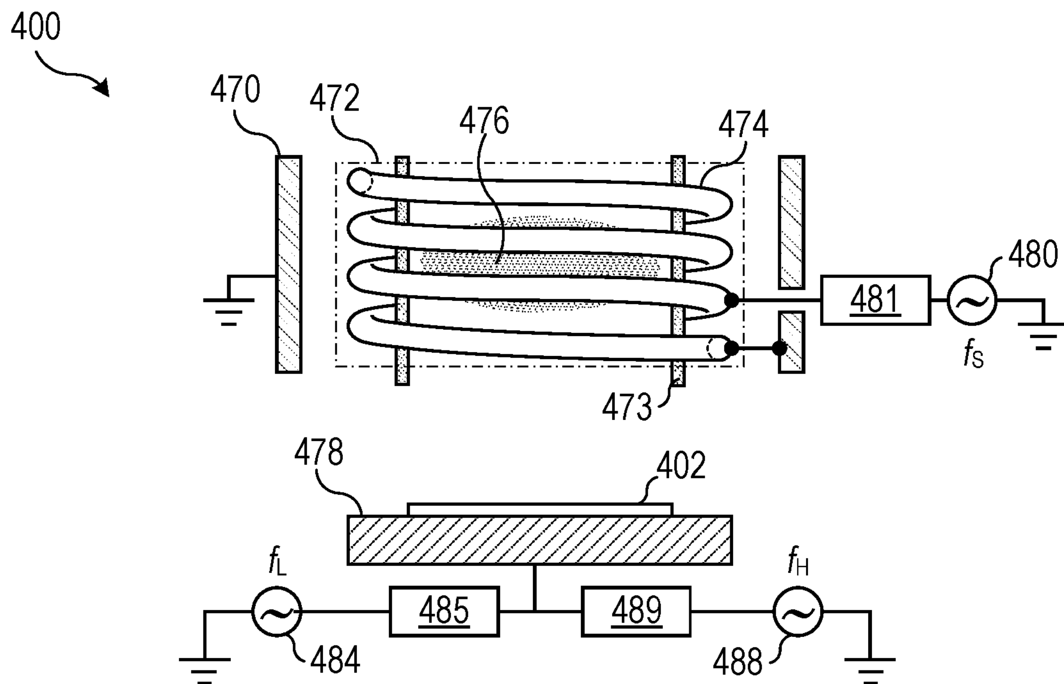


FIG. 4

FIG. 5

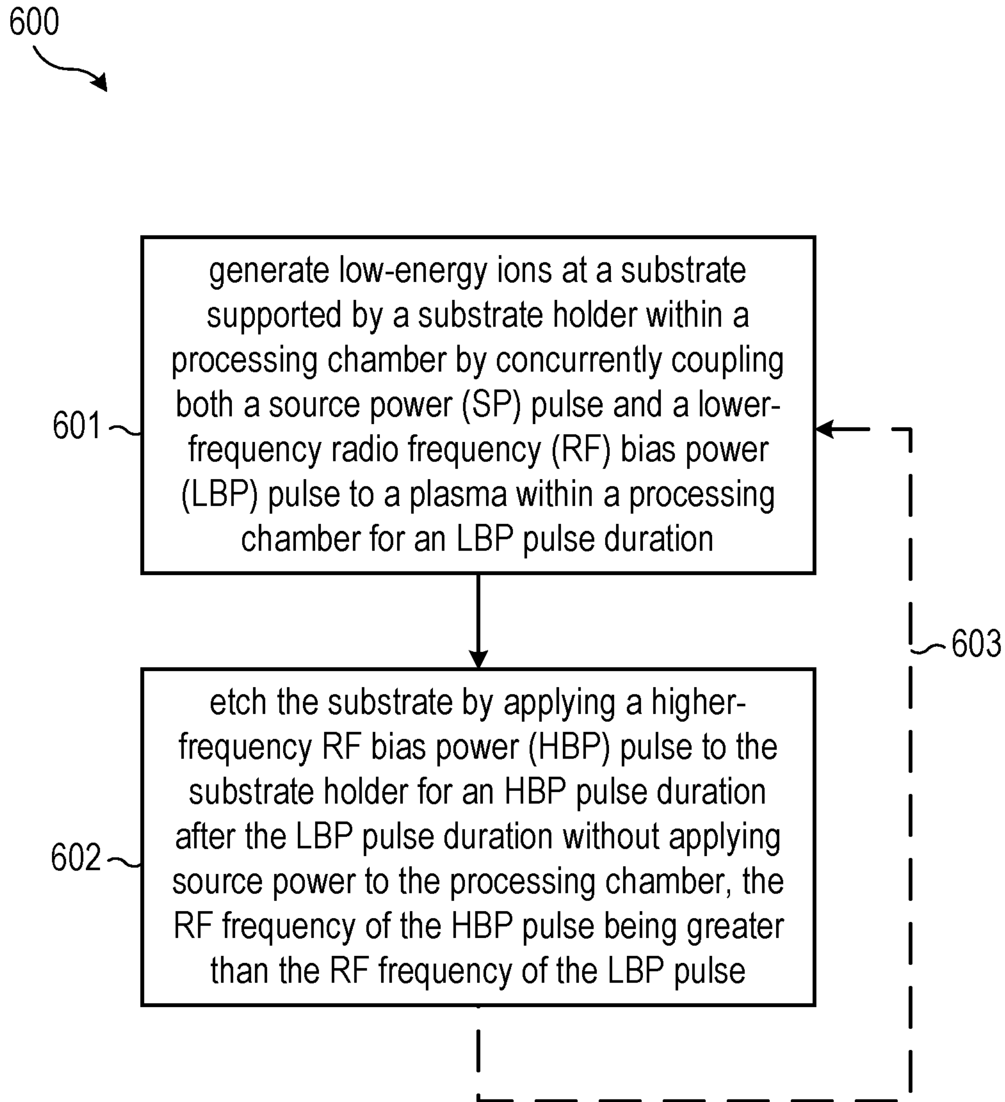


FIG. 6

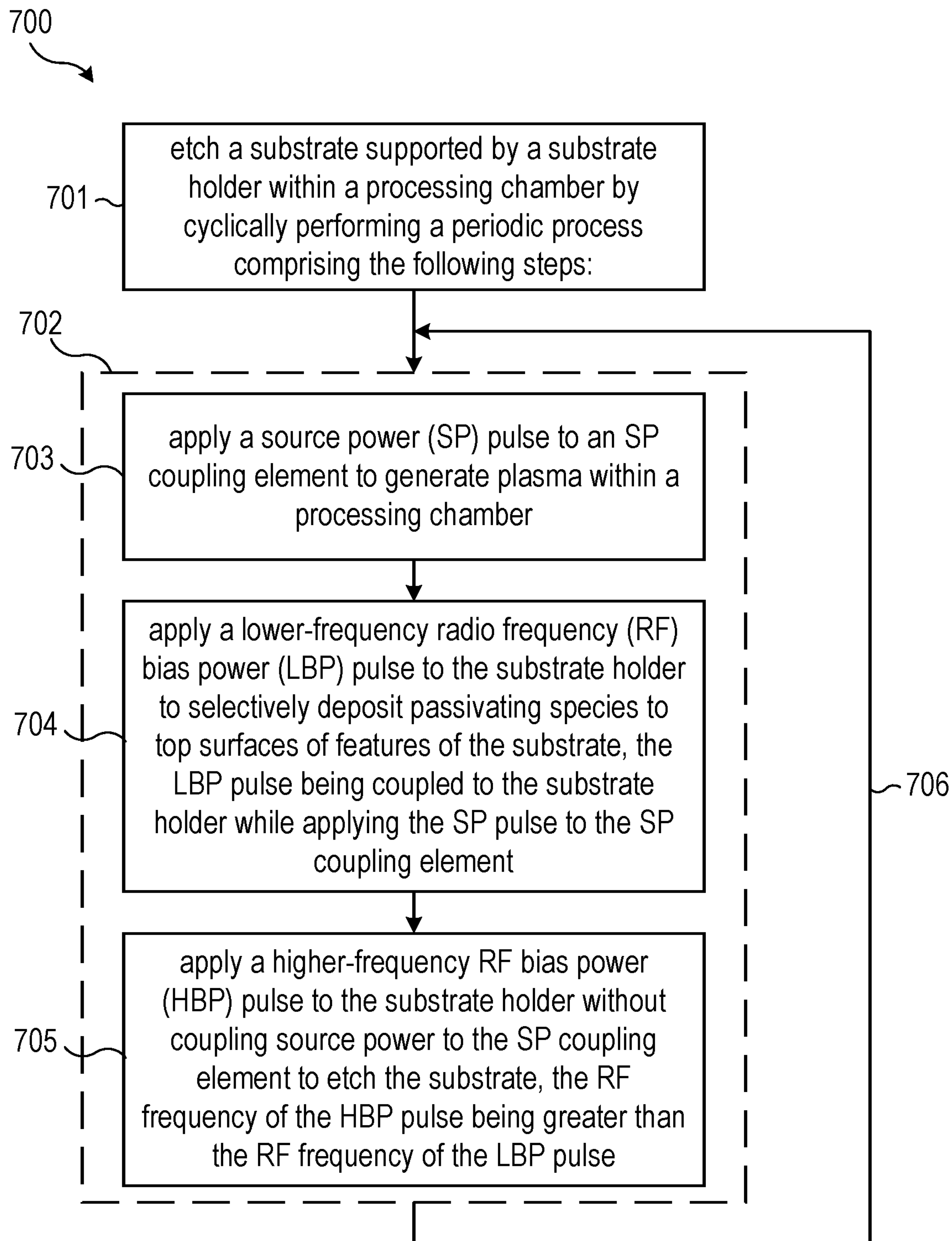


FIG. 7

PLASMA PROCESSING METHODS USING MULTIPHASE MULTIFREQUENCY BIAS PULSES

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] This application claims priority to U.S. Provisional Application No. 63/344,595, filed on May 22, 2022, which application is hereby incorporated by reference in its entirety.

TECHNICAL FIELD

[0002] The present invention relates generally to plasma processing, and, in particular embodiments, to plasma processing methods, apparatuses, and systems using multiphase multifrequency bias pulses.

BACKGROUND

[0003] Device formation within microelectronic workpieces can involve a series of manufacturing techniques including formation, patterning, and removal of a number of layers of material on a substrate. In order to achieve the physical and electrical specifications of current and next generation semiconductor devices, processing flows enabling reduction of feature size while maintaining structural integrity is desirable for various patterning processes. As device structures densify and develop vertically, the desire for precision material processing becomes more compelling.

[0004] Plasma processes are commonly used to form devices, interconnects, and contacts in microelectronic workpieces. For example, plasma etching and plasma deposition are common process steps during semiconductor device fabrication. A combination of source power (SP) applied to a coupling element and bias power (BP) applied to a substrate holder can be used to generate and direct plasma. Various conditions during a plasma process may influence whether material is being deposited onto a substrate, etched from the substrate, or a combination of the two.

[0005] However, conventional plasma processes fail to independently control etching and deposition during plasma processes resulting in reduced control and precision of the processes. For example, in the specific example of etching processes, some deposition can be useful to protect features that are not the target of the etch. But because conventional plasma processes lack independent and precise control over both deposition and etching, these features are insufficiently protected. Thus, material is undesirably removed from the features causing imperfections in feature profile such as recesses in the tops of features and necking, among others. Therefore, plasma processing methods that enable independent control over deposition and etching may be desirable.

SUMMARY

[0006] In accordance with an embodiment of the invention, a plasma processing method includes generating a plasma within a processing chamber using source power to ignite a glow phase of the plasma, generating low-energy ions at a substrate supported by a substrate holder in the processing chamber from the plasma using lower-frequency radio frequency (RF) bias power (LBP) applied during the glow phase, and generating high-energy ions at the substrate using higher-frequency RF bias power (HBP) applied during an afterglow phase of the plasma. The RF frequency of the HBP is greater than the RF frequency of the LBP.

[0007] In accordance with another embodiment of the invention, a plasma etching method includes generating low-energy ions at a substrate supported by a substrate holder within a processing chamber by concurrently coupling both a source power (SP) pulse and an LBP pulse to a plasma within a processing chamber for an LBP pulse duration, and etching the substrate by applying an HBP pulse to the substrate holder for an HBP pulse duration after the LBP pulse duration without applying source power to the processing chamber. The RF frequency of the HBP pulse is greater than the RF frequency of the LBP pulse.

[0008] In accordance with still another embodiment of the invention, a plasma processing method includes etching a substrate supported by a substrate holder within a processing chamber by cyclically performing a periodic process comprising the following steps: applying an SP pulse to an SP coupling element to generate plasma within a processing chamber; applying an LBP pulse to the substrate holder to selectively deposit passivating species to top surfaces of features of the substrate; and applying an HBP pulse to the substrate holder without coupling source power to the SP coupling element to etch the substrate. The LBP pulse is coupled to the substrate holder while applying the SP pulse to the SP coupling element. The RF frequency of the HBP pulse is greater than the RF frequency of the LBP pulse.

BRIEF DESCRIPTION OF THE DRAWINGS

[0009] For a more complete understanding of the present invention, and the advantages thereof, reference is now made to the following descriptions taken in conjunction with the accompanying drawings, in which:

[0010] FIGS. **1**A and **1**B illustrate an example plasma processing method in accordance with embodiments of the invention, where FIG. **1**A illustrates a schematic timing diagram of the plasma processing method and FIG. **1**B illustrates a corresponding target substrate;

[0011] FIG. **2** illustrates a schematic timing diagram and a corresponding target substrate of another example plasma processing method in accordance with embodiments of the invention;

[0012] FIG. **3** illustrates a schematic timing diagram of still another example plasma processing method in accordance with embodiments of the invention;

[0013] FIG. **4** illustrates a schematic diagram of an example plasma processing apparatus in accordance with embodiments of the invention;

[0014] FIG. **5** illustrates an example method of plasma processing in accordance with embodiments of the invention;

[0015] FIG. **6** illustrates another example method of plasma processing in accordance with embodiments of the invention; and

[0016] FIG. **7** illustrates an example method of plasma processing in accordance with embodiments of the invention.

[0017] Corresponding numerals and symbols in the different figures generally refer to corresponding parts unless otherwise indicated. The figures are drawn to clearly illustrate the relevant aspects of the embodiments and are not

necessarily drawn to scale. The edges of features drawn in the figures do not necessarily indicate the termination of the extent of the feature.

DETAILED DESCRIPTION OF ILLUSTRATIVE EMBODIMENTS

[0018] The making and using of various embodiments are discussed in detail below. It should be appreciated, however, that the various embodiments described herein are applicable in a wide variety of specific contexts. The specific embodiments discussed are merely illustrative of specific ways to make and use various embodiments, and should not be construed in a limited scope.

[0019] Both the source power and bias power may be supplied as radio frequency (RF) power to the processing chamber of a plasma processing apparatus. Pulsed plasma processing methods supply one or both of the RF source power and RF bias power to a processing chamber as pulses rather than as continuous wave power. For example, BP pulses may be provided synchronously or asynchronously with SP pulses. Such existing synchronous/asynchronous schemes often use a single RF frequency for the bias power, even when supplying the bias power asynchronously (e.g. single frequency, dual-phase), and are not adequate to independently control etching and deposition.

[0020] Some conventional methods mix RF frequencies to shape the waveform of the BP pulses, but such methods are employed to influence plasma uniformity and do not afford independent control over deposition and etching.

[0021] Other conventional methods supply BP pulses with high RF frequency and high power along with the SP pulses and low RF frequency, low power BP pulses with very short duration in between SP pulses to avoid plasma generation and heating. However, the high RF frequency BP pulses may not allow fine control over deposition while the source power is due to generation of high-energy ions with significant verticality. Meanwhile, the low RF frequency BP pulses are intended to minimize any disruption to the plasma structure and therefore may lack the flexibility necessary for full control over etching.

[0022] In various embodiments, plasma processing methods described herein apply BP pulses with multiple RF frequencies across multiple phases. Unlike conventional methods, this multiphase, multifrequency bias pulsing may advantageously facilitate independent control over deposition and etching during a plasma process. For example, passivating species may be deposited with precision using lower-frequency RF bias power applied prior to an etch phase that uses higher-frequency RF bias power. Tune of pulse durations and frequencies may afford the ability to optimize deposition to within 2-3 atoms (e.g. approaching monolayer) variation, for example. In this way, Separate etching and deposition phases may be advantageously realized in one pulsing scheme.

[0023] This may have the advantage allowing features to be adequately protected during etching phases of the plasma process. The lower-frequency RF bias power may be applied concurrently with source power to generate low-energy ions at a substrate. The low-energy ions may have the benefit of being substantially thermal allowing the selective deposition of passivating species at top surfaces of features through ion-assisted deposition mechanisms.

[0024] For example, in the specific application of a soft-landing step for gate etching a FinFET device, a highly anisotropic etch profile may be achieved without significant damage to the fin. This may be particularly beneficial since device performance is strongly dependent on fin shape (e.g. the amount of fin recess). With the plasma processing methods described herein, fin recess may be advantageously reduced (e.g. by 45%) over conventional continuous wave or single frequency processes.

[0025] Embodiments provided below describe various plasma processing methods, apparatuses, and systems, and in particular, that include plasma processing methods, apparatuses, and systems using multiphase multifrequency bias pulses that apply lower-frequency RF bias power during a deposition phase and higher-frequency RF bias power during an etch phase. The following description describes the embodiments. FIGS. **1**A and **1**B, showing a schematic timing diagram and a corresponding target substrate, are used to describe an embodiment plasma processing method. Two additional embodiment plasma processing methods are described using FIGS. **2** and **3**. An embodiment plasma processing apparatus is described using FIG. **4**. Three embodiment methods of plasma processing are described using FIGS. **5**-**7**.

[0026] FIGS. **1**A and **1**B illustrate an example plasma processing method in accordance with embodiments of the invention, where FIG. **1**A illustrates a schematic timing diagram of the plasma processing method and FIG. **1**B illustrates a corresponding target substrate.

[0027] Referring to FIG. **1**A, a plasma processing method wo includes a first phase 1 during which an SP pulse with an RF frequency f_S and an SP pulse duration t_S is applied concurrently with a BP pulse with lower-frequency RF frequency f_L (an LBP pulse) for an LBP pulse duration t_L. In some embodiments, SP pulse duration t_S fully overlaps the LBP pulse duration t_L and t_S is equal to t_L in one embodiment. As shown, the SP pulse duration t_S may precede the application of the LBP pulse. Additionally, in some cases the SP pulse duration is may extend past the end of the LBP pulse.

[0028] The plasma processing method **100** further includes a second phase 2 during which an HBP pulse with higher-frequency RF frequency f_H (an HBP pulse) for an HBP pulse duration t_H. The application of the HBP pulse occurs after the first phase 1. In one embodiment, the HBP pulse is applied directly after the end of the SP pulse. In other embodiments, a delay may be introduced between the SP pulse and the HBP pulse.

[0029] The LBP pulse frequency f_L is less than the HBP pulse frequency f_H. In some embodiments the LBP pulse frequency f_L is less than about 2 MHz. For example, f_L may be between about 0.4 to about 2 MHz, but lower frequencies are of course possible. In one embodiment, the LBP pulse frequency f_L is about 1.2 MHz.

[0030] In contrast, the HBP pulse frequency f_H is greater than about 3 MHz in some embodiments. In various embodiments, f_H is in the high frequency (HF) band of the electromagnetic spectrum ranging from 3 MHz to 30 MHz. However, the HBP pulse frequency f_H may also be higher, such as in the very high frequency (VHF) band, the ultra high frequency (UHF) band, and others. In one embodiment, f_H is about 13 MHz (e.g. 13.56 MHz).

[0031] Although there is no requirement that the RF frequency of the SP pulse f_S be any particular frequency, it may be higher than both f_H and f_L in some embodiments. For example, f_S may be in the HF band, the VHF band, the UHF

band, and above. In one embodiment, the RF frequency of the SP pulse f_S is about 26 MHz. In another embodiment, the RF frequency of the SP pulse f_S is about 13 MHz (e.g. 13.56 MHz).

[0032] The plasma processing method **100** does not rely on any specific power level values for the SP pulse, the LBP pulse, or the HBP pulse. However, as shown, in the first phase 1, the SP power level P_{S1} and LBP power level P_{L1} are greater than zero while the HBP power level P_{H1} is zero. Similarly, in the second phase 2, the HBP power level P_{H2} is greater than zero while the SP power level P_{S2} and the LBP power level P_{L2} are reduced (e.g. to zero as depicted, but this is not a strict requirement).

[0033] Referring now to FIG. **1**B, the first phase 1 may be a deposition phase and may be characterized by the generation of low-energy ions **164** at a workpiece **102**. The workpiece **102** includes a substrate **160**. The substrate **106** may be any suitable substrate for which plasma processing is desired. The low-energy ions **164** may facilitate the deposition of a passivating layer **162**. The passivating layer **162** may be advantageously selectively deposited at top surfaces **163** of features of the substrate **160**. For example, the low-energy ions **164** may be substantially thermal resulting in reduced penetration into narrow features of the substrate **160** which may result in the desired selective behavior. In some embodiments, the features of the substrate **160** are fins and the plasma processing method **200** is a gate etch (a soft-landing step for gate etching in one particular embodiment).

[0034] The second phase 2 may be an etching phase and include high-energy ions **166**. The high-energy ions **166** may have considerable vertical velocity compared to the near-thermal low-energy ions **164** of the first phase 1. This verticality of the high-energy ions **166** may result in etching of the substrate to an etch depth **168**. Because the high-energy ions **166** are substantially vertical, they reach the bottom of the features with minimal undesirably interaction with sidewalls. However, the top surfaces **163** of the features are exposed to the high-energy ions **166**. The selective deposition of the passivating layer **162** may advantageously protect the top surfaces **163** of features from undesirable effects such as recess.

[0035] FIG. **2** illustrates a schematic timing diagram and a corresponding target substrate of another example plasma processing method in accordance with embodiments of the invention. The plasma processing method of FIG. **2** may be a specific implementation of other plasma processing methods described herein such as the plasma processing method of FIG. **1**, for example. Similarly labeled elements may be as previously described.

[0036] Referring to FIG. **2**, a plasma processing method **200** includes SP pulses, LBP pulses, and HBP pulses applied at respective frequencies and durations to process a workpiece **202**. It should be noted that here and in the following a convention has been adopted for brevity and clarity wherein elements adhering to the pattern [x02] may be related implementations of a workpiece in various embodiments. For example, the workpiece **202** may be similar to the workpiece **102** except as otherwise stated. An analogous convention has also been adopted for other elements as made clear by the use of similar terms in conjunction with the aforementioned three-digit numbering system.

[0037] The plasma processing method **200** is a cyclical process where the cycle **250** is repeated until the desired processing effect is achieved (e.g. etching regions of a substrate **260** to a desired depth). Each cycle **250** includes a glow phase **240** and an afterglow phase **245** which corresponds with the application of the SP pulse. That is, during the SP pulse duration t_S, plasma (e.g. a high density plasma) in a glow phase is generated which rapidly transitions into an afterglow phase after the SP pulse (i.e. the source power is removed).

[0038] During the glow phase **240** caused the SP pulse, an LBP pulse is applied during a low-energy ion generation phase **210**. Optionally, the SP pulse may begin before the LBP pulse resulting in a plasma generation phase **205** during which no LBP is applied. When the SP pulse extends beyond the LBP pulse, a redeposition phase **215** is created.

[0039] The HBP pulse is applied in an etch phase **220** during the afterglow phase **245**. An optional delay phase **217** may be utilized as part of the afterglow phase **245** to delay the application of the HBP pulse after the SP pulse ends (e.g. to allow the plasma to cool a desired amount). Also in the afterglow phase **245**, an optional pumping phase **230** may be included to remove by-products in preparation for the next glow phase **240**.

[0040] During the cycle **250** the plasma processing method **200** iterates through a deposition phase (divided into sub-phases 1-a and 1-b) and an etching phase 2. As shown, the substrate **260** of the workpiece **202** (which may include an underlying layer **261**). In phase 1-a, low-energy ions **264** are generated at the substrate **260** which assist in deposition of a passivating layer **262** on surfaces of the substrate **260**. As before, the passivating layer **262** is selectively deposited at top surfaces **263** of features of the substrate **260** (e.g. fins). In phase 1-b, deposition continues as by-products **265** (e.g. from mild etching by the low-energy ions **264**) are dissociated and redeposited.

[0041] The buildup of the passivating layer **262** protects the features in phase 2 while high-energy ions **266** reach the bottom of the features and etch the substrate **260** to a first etch depth **268**. In this example, the first etch depth **268** is not an end point of the plasma processing method **200**. As illustrated, phases 1-a, 1-b, and 2 are repeated to etch the substrate **260** to a second etch depth **269**. For the purposes of illustration, this may be the end point of the plasma processing method **200** as the underlying layer **261** has been reached (although etching through the underlying layer is also possible). The number of iterations of the cycle **250** may more than two (e.g. much more) and will depend on the specific details of a given application.

[0042] FIG. **3** illustrates a schematic timing diagram of yet another example plasma processing method in accordance with embodiments of the invention. The plasma processing method of FIG. **3** may be a specific implementation of other plasma processing methods described herein such as the plasma processing method of FIG. **1**, for example. Similarly labeled elements may be as previously described.

[0043] Referring to FIG. **3**, a plasma processing method **300** includes a cycle **350** which includes a glow phase **340** and an afterglow phase **345**. The plasma processing method **300** may be a specific implementation of the plasma processing method **200** of FIG. **2**, for example, in which relative power levels and duty cycles (i.e. percentage of on time of a pulse during a cycle) of the SP pulses, LBP pulses, and HBP pulses are provided.

[0044] In this specific example, the LBP power level P_L during the low-energy ion generation phase **340** is much less

than the HBP power level P_H during the etch phase **320**. For example, P_H may be at least three times P_L as shown. In one embodiment, P_H is twelve times P_L. In various embodiments, P_L is less than about 100 W and is about 50 W in one embodiment. Similarly, in various embodiments, P_H is greater than about 250 W (e.g. between 250 W and moo W, although higher is possible). In one embodiment, P_H is about 600 W.

[0045] The SP power level P_S is in between the LBP power level P_L and the HBP power level P_H in this example. For example, P_S may be about half of P_H in some implementations. In various embodiments, P_S is greater than about 200 W is about 300 W in one embodiment.

[0046] In this specific implementation, the duration of the delay phase is zero resulting in the etch phase **320** immediately following the redeposition phase **315**. The optional pumping phase **330** is utilized and has a pumping duration t_P corresponding to an off time that has a duty cycle of 60% (i.e. 60% of each iterated cycle **350**). Comparatively, the duty cycle of both the LBP pulse is 10% and the HBP pulse is 10% while the duty cycle of the SP pulse is 30%.

[0047] Of course, the specifics of these duty cycles and the pulse delays within the cycle will depend on the specific details of a given application. Further, the duty cycles, power levels, frequencies, delays, and other parameters may be made dynamic if desired (varying from cycle to cycle within the same plasma processing method).

[0048] FIG. **4** illustrates a schematic diagram of an example plasma processing apparatus in accordance with embodiments of the invention. The plasma processing apparatus of FIG. **4** may be used to perform the plasma processing methods described herein, such as the plasma processing method of FIG. **1**, for example. Similarly labeled elements may be as previously described.

[0049] Referring to FIG. **4**, a plasma processing system **400** includes a grounded outer structure **470** surrounding a SP coupling electrode **472** (which may be implemented as a helical resonator antenna **474** which in turn surrounds a dielectric inner surface **473**). The helical resonator antenna **474** may be grounded at one end and left free at the other. An RF source power supply **480** is coupled to a SP generator circuit **481** which is in turn coupled to the helical resonator antenna **474** at an appropriate distance from the grounded connection.

[0050] The source power coupling location (which may also be referred to as a tap position) may depend on operating frequency as well as other considerations. A plasma **476** (which may be a high-density plasma such as a helical resonator plasma as shown) is generated which is inductively coupled to the SP coupling electrode **472**. For example, the dielectric inner surface **473** may be provided between the plasma **476** and the helical resonator antenna **474** to facilitate inductive coupling. An RF LBP supply **484** may be coupled to an LBP generator circuit **485** which is coupled to a substrate support **478** (e.g. a lower plate electrode (LEL). The substrate support **478** may serve as an electrostatic chuck (ESC) to support and retain a substrate **402**.

[0051] The helical resonator antenna **474** may be a full-wave, half-wave, or quarter-wave antenna. For example, if the helical resonator antenna **474** is driven at using RF power with a frequency of about 26 MHz, a quarter-wave helical resonator antenna may be about 2.25 m in length. Similarly, if the helical resonator antenna **474** is driven at using RF power with a frequency of 13.56 MHz, a quarter-wave helical resonator antenna may be about 5.5 m in length. As the RF frequency increases, the length of the helical resonator antenna **474** may decrease. For example, a quarter-wave helical resonator antenna driven at about 50 MHz may be about 1.5 m in length.

[0052] FIG. **5** illustrates an example method of plasma processing in accordance with embodiments of the invention. The method of FIG. **5** may be combined with other methods and performed using the systems and apparatuses as described herein. For example, the method of FIG. **5** may be combined with any of the embodiments of FIGS. **1**A, **1**B, and **2**-**4**. Although shown in a logical order, the arrangement and numbering of the steps of FIG. **5** are not intended to be limited. The method steps of FIG. **5** may be performed in any suitable order or concurrently with one another as may be apparent to a person of skill in the art.

[0053] Referring to FIG. **5**, a method **500** of plasma processing includes step **501** of generating a plasma within a processing chamber using source power to ignite a glow phase of the plasma. During the glow phase of the plasma, low-energy ions are generated at a substrate supported by a substrate holder in the processing chamber from the plasma using lower-frequency RF bias power in step **502**.

[0054] After the glow phase (i.e. after the source power has been removed), the plasma is in an afterglow phase. Step **503** is to generate high-energy ions at the substrate using higher-frequency RF bias power applied during the afterglow phase of the plasma. The RF frequency of the higher-frequency RF bias power (e.g. in the HF band ranging from 3 MHz to 30 MHz) is greater than the RF frequency of the lower-frequency RF bias power (e.g. less than about s MHz). Optionally, step **501**, step **502**, and step **503** may then be repeated, shown as step **504**, for some number of times to achieve a desired result (i.e. cyclically performed as a cycle).

[0055] FIG. **6** illustrates another example method of plasma processing in accordance with embodiments of the invention. The method of FIG. **6** may be combined with other methods and performed using the systems and apparatuses as described herein. For example, the method of FIG. **6** may be combined with any of the embodiments of FIGS. **1**A, **1**B, and **2**-**4**. Additionally, the method of FIG. **6** may be combined with other methods, such as the method of FIG. **5**, for example. Although shown in a logical order, the arrangement and numbering of the steps of FIG. **6** are not intended to be limited. The method steps of FIG. **6** may be performed in any suitable order or concurrently with one another as may be apparent to a person of skill in the art.

[0056] Referring to FIG. **6**, a method **600** of plasma etching includes step **601** of generating low-energy ions at a substrate supported by a substrate holder within a processing chamber. The low-energy ions are generated by concurrently coupling both a source power pulse and a lower-frequency RF bias power pulse to a plasma within a processing chamber for a first pulse duration.

[0057] After the low-energy ions are generated, the substrate is etched in step **602** by applying a higher-frequency RF bias power pulse to the substrate holder for a second pulse duration after the first pulse duration. The higher-frequency RF bias power pulse is applied without applying source power to the processing chamber.

[0058] The RF frequency of the higher-frequency RF bias power (e.g. in the HF band ranging from 3 MHz to 30 MHz) is greater than the RF frequency of the lower-frequency RF

bias power (e.g. less than about s MHz). Optionally, step **501**, step **502**, and step **503** may then be repeated, shown as step **504**, for some number of times to achieve a desired result (i.e. cyclically performed as a cycle). Optional step **603** is to repeat step **601** and step **602** for some number of times to achieve a desired result (i.e. cyclically performed as a cycle).

[0059] FIG. **7** illustrates an example method of plasma processing in accordance with embodiments of the invention. The method of FIG. **7** may be combined with other methods and performed using the systems and apparatuses as described herein. For example, the method of FIG. **7** may be combined with any of the embodiments of FIGS. **1**A, **1**B, and **2**-**4**. Additionally, the method of FIG. **7** may be combined with other methods, such as either of the methods of FIGS. **5** and **6**, for example. Although shown in a logical order, the arrangement and numbering of the steps of FIG. **7** are not intended to be limited. The method steps of FIG. **7** may be performed in any suitable order or concurrently with one another as may be apparent to a person of skill in the art.

[0060] Referring to FIG. **7**, a method **700** of plasma etching includes step **701** of etching a substrate supported by a substrate holder within a processing chamber by cyclically performing **706** a periodic process **702**. The periodic process **702** includes step **703**, step **704**, and step **705**.

[0061] Step **703** is to apply a source power pulse to a source power coupling element to generate plasma within a processing chamber. In step **704**, a lower-frequency RF bias power pulse is applied to the substrate holder to selectively deposit passivating species to top surfaces of features of the substrate. The lower-frequency RF bias power pulse is coupled to the substrate holder while applying the SP pulse to the SP coupling element.

[0062] A higher-frequency RF bias power pulse is applied to the substrate holder without coupling source power to the source power coupling element to etch the substrate in step **705**. The RF frequency of the higher-frequency RF bias power (e.g. in the HF band ranging from 3 MHz to 30 MHz) is greater than the RF frequency of the lower-frequency RF bias power (e.g. less than about 2 MHz).

[0063] Example embodiments of the invention are summarized here. Other embodiments can also be understood from the entirety of the specification as well as the claims filed herein.

[0064] Example 1. A plasma processing method including: generating a plasma within a processing chamber using source power to ignite a glow phase of the plasma; generating low-energy ions at a substrate supported by a substrate holder in the processing chamber from the plasma using lower-frequency RF bias power (LBP) applied during the glow phase; and generating high-energy ions at the substrate using higher-frequency RF bias power (HBP) applied during an afterglow phase of the plasma, the RF frequency of the HBP being greater than the RF frequency of the LBP.

[0065] Example 2. The plasma processing method of example 1, where generating the glow phase includes applying source power to generate the plasma prior to generating the low-energy ions and continuing to apply the source power while generating the low-energy ions.

[0066] Example 3. The plasma processing method of examples 1 and 2, where generating the glow phase includes applying source power to dissociate and redeposit etching by-products after generating the low-energy ions and before generating the high-energy ions.

[0067] Example 4. The plasma processing method of one of examples 1 to 3, where the RF frequency of the LBP is less than about 2 MHz; and where the RF frequency of the HBP is in the high frequency (HF) band ranging from 3 MHz to 30 MHz.

[0068] Example 5. The plasma processing method of example 4, where the power level of the LBP is less than about wo W; and where the power level of the HBP is at least about three times the power level of the LBP.

[0069] Example 6. A plasma etching method including: generating low-energy ions at a substrate supported by a substrate holder within a processing chamber by concurrently coupling both an SP pulse and an LBP pulse to a plasma within a processing chamber for an LBP pulse duration; and etching the substrate by applying an HBP pulse to the substrate holder for an HBP pulse duration after the LBP pulse duration without applying source power to the processing chamber, the RF frequency of the HBP pulse being greater than the RF frequency of the LBP pulse.

[0070] Example 7. The plasma etching method of example 6, further including: applying no source power or bias power to the processing chamber for a delay duration after the LBP duration and before the HBP duration.

[0071] Example 8. The plasma etching method of one of examples 6 and 7, further including: applying the SP pulse to an SP coupling element before the LBP pulse duration to generate the plasma.

[0072] Example 9. The plasma etching method of one of examples 6 to 8, further including: applying the SP pulse to the plasma for an SP duration after the LBP pulse duration and before the HBP pulse duration.

[0073] Example 10. The plasma etching method of one of examples 6 to 9, where the RF frequency of the LBP pulse is less than about 2 MHz.

[0074] Example 11. The plasma etching method of example 10, where the RF frequency of the LBP pulse is about 1.2 MHz.

[0075] Example 12. The plasma etching method of one of examples 6 to 11, where the power level of the LBP pulse is less than about wo W.

[0076] Example 13. The plasma etching method of example 12, where the power level of the HBP pulse is greater than the power level of the LBP pulse, the power level of the SP pulse being therebetween.

[0077] Example 14. A plasma processing method including etching a substrate supported by a substrate holder within a processing chamber by cyclically performing a periodic process including the following steps: applying an SP pulse to an SP coupling element to generate plasma within a processing chamber; applying an LBP pulse to the substrate holder to selectively deposit passivating species to top surfaces of features of the substrate, the LBP pulse being coupled to the substrate holder while applying the SP pulse to the SP coupling element; and applying an HBP pulse to the substrate holder without coupling source power to the SP coupling element to etch the substrate, the RF frequency of the HBP pulse being greater than the RF frequency of the LBP pulse.

[0078] Example 15. The plasma processing method of example 14, where applying the LBP pulse to the substrate to selectively deposit the passivating species includes: applying the LBP pulse to the substrate while applying the

SP pulse to generate low-energy ions at the substrate; and continuing to apply the SP pulse to an SP coupling element after applying the LBP pulse to dissociate species for deposition as passivating species to the top surfaces of the features of the substrate.

[0079] Example 16. The plasma processing method of example 15, where the periodic process further includes: applying no source power or bias power to the processing chamber for a predetermined duration after applying the HBP pulse to the substrate holder.

[0080] Example 17. The plasma processing method of example 16, where the SP pulse is periodically applied during the periodic process with a duty cycle of less than 50%; and where both the LBP pulse and the HBP pulse are periodically applied during the periodic process with respective duty cycles of less than 25%.

[0081] Example 18. The plasma processing method of example 17, where the period of the periodic process is between about 1 ms and about 100 ms.

[0082] Example 19. The plasma processing method of one of examples 14 to 18, where the RF frequency of the LBP pulse is less than about 2 MHz.

[0083] Example 20. The plasma processing method of example 19, where the power level of the LBP pulse is less than about 100 W; and where the power level of the HBP pulse is greater than the power level of the LBP pulse, the power level of the SP pulse being therebetween.

[0084] While this invention has been described with reference to illustrative embodiments, this description is not intended to be construed in a limiting sense. Various modifications and combinations of the illustrative embodiments, as well as other embodiments of the invention, will be apparent to persons skilled in the art upon reference to the description. It is therefore intended that the appended claims encompass any such modifications or embodiments.

What is claimed is:

1. A plasma processing method comprising:

generating a plasma within a processing chamber using source power to ignite a glow phase of the plasma;

generating low-energy ions at a substrate supported by a substrate holder in the processing chamber from the plasma using lower-frequency radio frequency (RF) bias power (LBP) applied during the glow phase; and

generating high-energy ions at the substrate using higher-frequency RF bias power (HBP) applied during an afterglow phase of the plasma, the RF frequency of the HBP being greater than the RF frequency of the LBP.

2. The plasma processing method of claim **1**, wherein generating the glow phase comprises applying source power to generate the plasma prior to generating the low-energy ions and continuing to apply the source power while generating the low-energy ions.

3. The plasma processing method of claim **1** wherein generating the glow phase comprises applying source power to dissociate and redeposit etching by-products after generating the low-energy ions and before generating the high-energy ions.

4. The plasma processing method of claim **1**,

wherein the RF frequency of the LBP is less than about 2 MHz; and

wherein the RF frequency of the HBP is in the high frequency (HF) band ranging from 3 MHz to 30 MHz.

5. The plasma processing method of claim **4**,

wherein the power level of the LBP is less than about 100 W; and

wherein the power level of the HBP is at least about three times the power level of the LBP.

6. A plasma etching method comprising:

generating low-energy ions at a substrate supported by a substrate holder within a processing chamber by concurrently coupling both a source power (SP) pulse and a lower-frequency radio frequency (RF) bias power (LBP) pulse to a plasma within a processing chamber for an LBP pulse duration; and

etching the substrate by applying a higher-frequency RF bias power (HBP) pulse to the substrate holder for an HBP pulse duration after the LBP pulse duration without applying source power to the processing chamber, the RF frequency of the HBP pulse being greater than the RF frequency of the LBP pulse.

7. The plasma etching method of claim **6**, further comprising:

applying no source power or bias power to the processing chamber for a delay duration after the LBP duration and before the HBP duration.

8. The plasma etching method of claim **6**, further comprising:

applying the SP pulse to an SP coupling element before the LBP pulse duration to generate the plasma.

9. The plasma etching method of claim **6**, further comprising:

applying the SP pulse to the plasma for an SP duration after the LBP pulse duration and before the HBP pulse duration.

10. The plasma etching method of claim **6**, wherein the RF frequency of the LBP pulse is less than about 2 MHz.

11. The plasma etching method of claim **10**, wherein the RF frequency of the LBP pulse is about 1.2 MHz.

12. The plasma etching method of claim **6**, wherein the power level of the LBP pulse is less than about 100 W.

13. The plasma etching method of claim **12**, wherein the power level of the HBP pulse is greater than the power level of the LBP pulse, the power level of the SP pulse being therebetween.

14. A plasma processing method comprising etching a substrate supported by a substrate holder within a processing chamber by cyclically performing a periodic process comprising the following steps:

applying a source power (SP) pulse to an SP coupling element to generate plasma within a processing chamber;

applying a lower-frequency radio frequency (RF) bias power (LBP) pulse to the substrate holder to selectively deposit passivating species to top surfaces of features of the substrate, the LBP pulse being coupled to the substrate holder while applying the SP pulse to the SP coupling element; and

applying a higher-frequency RF bias power (HBP) pulse to the substrate holder without coupling source power to the SP coupling element to etch the substrate, the RF frequency of the HBP pulse being greater than the RF frequency of the LBP pulse.

15. The plasma processing method of claim **14**, wherein applying the LBP pulse to the substrate to selectively deposit the passivating species comprises:

applying the LBP pulse to the substrate while applying the SP pulse to generate low-energy ions at the substrate; and

continuing to apply the SP pulse to an SP coupling element after applying the LBP pulse to dissociate species for deposition as passivating species to the top surfaces of the features of the substrate.

16. The plasma processing method of claim **15**, wherein the periodic process further comprises:

applying no source power or bias power to the processing chamber for a predetermined duration after applying the HBP pulse to the substrate holder.

17. The plasma processing method of claim **16**,

wherein the SP pulse is periodically applied during the periodic process with a duty cycle of less than 50%; and

wherein both the LBP pulse and the HBP pulse are periodically applied during the periodic process with respective duty cycles of less than 25%.

18. The plasma processing method of claim **17**, wherein the period of the periodic process is between about 1 ms and about 100 ms.

19. The plasma processing method of claim **14**, wherein the RF frequency of the LBP pulse is less than about 2 MHz.

20. The plasma processing method of claim **19**,

wherein the power level of the LBP pulse is less than about 100 W; and

wherein the power level of the HBP pulse is greater than the power level of the LBP pulse, the power level of the SP pulse being therebetween.

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