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Systems and Methods for Use of Low Frequency Harmonics in Bias Radiofrequency Supply to Control Uniformity of Plasma Process Results Across Substrate

Abstract

First, second, third, and fourth radiofrequency (RF) signal generators generate first, second, third, and fourth RF signals, respectively, having first, second, third, and fourth frequencies, respectively. The second and third frequencies are different specified harmonics of the first frequency. The fourth frequency is at least two orders of magnitude larger than the first frequency. An impedance matching system controls impedances for the first, second, third, and fourth RF signal generators. A control module is programmed to control: A) a first phase difference between the first and second RF signals, B) a second phase difference between the first and third RF signals, C) a first voltage difference between the first and second RF signals, D) a second voltage difference between the first and third RF signals. The first and second phase differences and the first and second voltage differences collectively control a plasma sheath voltage as a function of time.

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Background/Summary

CLAIM OF PRIORITY [0001] This application is a continuation application under 35 U.S.C. 120 of prior U.S. patent application Ser. No. 18/010,900, filed on Dec. 16, 2022, which is a national stage filing of and claims priority under 35 U.S.C. 371 to International Application No. PCT/US2021/038647, filed on Jun. 23, 2021, which claims the benefit of U.S. Provisional Patent Application No. 63/044,827, filed on Jun. 26, 2020. The entire disclosure of each application referenced above is incorporated herein by reference.

BACKGROUND
1. Field of the Disclosure
[0002] The present disclosure relates to semiconductor device fabrication.
2. Description of the Related Art
[0003] In the fabrication of semiconductor devices such as integrated circuits, memory cells, and the like, a series of manufacturing operations are performed to define features on a semiconductor wafer ("wafers" hereafter). The wafer includes integrated circuit devices in the form of multi-level structures defined on a silicon substrate. At a substrate level, transistor devices with diffusion regions are formed. In subsequent levels, interconnect metallization lines are patterned and electrically connected to the transistor devices to define a desired integrated circuit device. Also, patterned conductive layers are insulated from other conductive layers by dielectric materials.
[0004] Many modern semiconductor chip fabrication processes include generation of a plasma from which ions and/or radical constituents are derived for use in either directly or indirectly affecting a change on a surface of a substrate exposed to the plasma. For example, various plasma-based processes can be used to etch material from a substrate surface, deposit material onto a substrate surface, or modify a material already present on a substrate surface. The plasma is often generated by applying radiofrequency (RF) power to a process gas in a controlled environment, such that the process gas becomes energized and transforms into the desired plasma. The characteristics of the plasma and corresponding process results on the substrate are affected by many process parameters including, but not limited to, material composition of the process gas, flow rate of the process gas, geometric features of the plasma generation region and surrounding structures, temperatures of the process gas and surrounding materials, frequency of the RF power applied, magnitude of the RF power applied, and temporal manner in which the RF power is applied, among others. Therefore, it is of interest to understand, monitor, and/or control some of the process parameters that may affect the characteristics of the generated plasma and corresponding process results on the substrate. It is within this context that the present disclosure arises.
SUMMARY
[0005] In an example embodiment, a radiofrequency (RF) signal supply system for a plasma processing system is disclosed. The RF signal supply system includes a first RF signal generator set to generate a first RF signal having a first frequency. The RF signal supply system also includes a second RF signal generator set to generate a second RF signal having a second frequency. The second frequency is a specified harmonic of the first frequency. The RF signal supply system also

includes a third RF signal generator set to generate a third RF signal having a third frequency. The third frequency is a specified harmonic of the first frequency. The third frequency and the second frequency are different specified harmonics of the first frequency. The RF signal supply system also includes a fourth RF signal generator set to generate a fourth RF signal having a fourth frequency. The fourth frequency is at least two orders of magnitude larger than the first frequency.
[0006] In an example embodiment, a method is disclosed for operating an RF signal supply system for a plasma processing system. The method includes operating a first RF signal generator to generate a first RF signal having a first frequency at an output of the first RF signal generator. The method also includes operating a second RF signal generator to generate a second RF signal having a second frequency at an output of the second RF signal generator. The second frequency is a specified harmonic of the first frequency. The method also includes operating a third RF signal generator to generate a third RF signal having a third frequency at an output of the third RF signal generator. The third frequency is a specified harmonic of the first frequency. The third frequency and the second frequency are different specified harmonics of the first frequency. The method also includes operating a fourth RF signal generator to generate a fourth RF signal having a fourth frequency at an output of the fourth RF signal generator. The fourth frequency is at least two orders of magnitude larger than the first frequency. The method also includes operating an impedance matching system to control impedances at the output of the first RF signal generator, at the output of the second RF signal generator, at the output of the third RF signal generator, and at the output of the fourth RF signal generator. The first RF signal, the second RF signal, the third RF signal, and the fourth RF signal are transmitted through the impedance matching system to a radiofrequency supply input of the plasma processing system to cause generation of a plasma within the plasma processing system. The method also includes operating a control module to control a first phase difference between the second RF signal and the first RF signal. The method also includes operating the control module to control a second phase difference between the third RF signal and the first RF signal. The method also includes operating the control module to control a first voltage difference between the second RF signal and the first RF signal. The method also includes operating the control module to control a second voltage difference between the third RF signal and the first RF signal. The first phase difference, the second phase difference, the first voltage difference, and the second voltage difference collectively control a plasma sheath voltage as a function of time within the plasma processing system.
[0007] Other aspects and advantages of the invention will become more apparent from the following detailed description, taken in conjunction with the accompanying drawings, illustrating by way of example the present invention.

Description

BRIEF DESCRIPTION OF THE DRAWINGS
[0008] FIG. **1** shows an RF signal supply system that includes a low frequency RF signal generator and a high frequency RF signal generator, in accordance with some embodiments.
[0009] FIG. **2** shows a diagram of the frequency tuning process, in accordance with some embodiments.
[0010] FIG. **3** shows various plots of normalized voltage and normalized current as a function of time as measured at the output of the impedance matching system, when the RF signal generation system is operating in accordance with the frequency tuning process of FIG. **2**, in accordance with some embodiments.
[0011] FIG. **4** shows an example of injecting higher order harmonic frequency signals in conjunction with the fundamental (base) frequency signal to generate a non-sinusoidal waveform shape, in accordance with some embodiments.

[0012] FIG. **5**A shows a composite signal waveform that is a combination of a fundamental (base) frequency signal and a third harmonic frequency signal of the fundamental (base) frequency signal and a fifth harmonic frequency signal of the fundamental (base) frequency signal, in accordance with some embodiments.
[0013] FIG. **5**B shows a composite signal waveform that is a combination of a fundamental (base) frequency signal and a second harmonic frequency signal of the fundamental (base) frequency signal and a fourth harmonic frequency signal of the fundamental (base) frequency signal, in accordance with some embodiments.
[0014] FIG. **5**C shows a composite signal waveform that is a combination of a fundamental (base) frequency signal and a second harmonic frequency signal of the fundamental (base) frequency signal and a third harmonic frequency signal of the fundamental (base) frequency signal, in accordance with some embodiments.
[0015] FIG. **6** shows a reference low frequency RF signal of sinusoidal shape, along with its harmonic frequency signal components, in accordance with some embodiments.
[0016] FIG. **7** shows a composite low frequency RF signal of substantially square shape formed by combining phase-aligned third and fifth harmonic frequency signals with a fundamental (base) frequency signal, in accordance with some embodiments.
[0017] FIG. **8** shows a composite low frequency RF signal of sloped square shape formed by combining phase-shifted third and fifth harmonic frequency signals with a fundamental (base) frequency signal, in accordance with some embodiments.
[0018] FIG. **9** shows a plot of average film thickness versus radial position across the substrate obtained by performing etching processes in accordance with the frequency tuning process of FIG. **2**, with each etching process using a different one of the reference sinusoidal low frequency RF signal of FIG. **6**, the composite square-shaped low frequency RF signal of FIG. **7**, and the composite sloped-square-shaped low frequency RF signal of FIG. **8**, in accordance with some embodiments.
[0019] FIG. **10** shows various waveform shapes that are obtained by combining the third harmonic frequency signal and the fifth harmonic frequency signal with the fundamental (base) frequency signal, and by shifting the phase of the third and fifth harmonic frequency signals relative to the phase of the fundamental (base) frequency signal by various amounts, in accordance with some embodiments.
[0020] FIG. **11** shows an RF signal supply system that includes the low frequency RF signal generator and the high frequency RF signal generator, as described with regard to FIG. **1**, and that further includes a plurality of harmonic frequency RF signal generators, in accordance with some embodiments.
[0021] FIG. **12** shows an example configuration of the impedance matching system, in accordance with some embodiments.
[0022] FIG. **13**A shows an example diagram of a CCP processing system, in accordance with some embodiments of the present disclosure.
[0023] FIG. **13**B shows an example diagram of an ICP processing system, in accordance with some embodiments of the present disclosure.
[0024] FIG. **13**C shows a top view of the coil, in accordance with some embodiments.
[0025] FIG. **13**D shows a diagram of the control module, in accordance with some example embodiments.
[0026] FIG. **14** shows a flowchart of a method for operating a radiofrequency signal generator system for a plasma processing system, in accordance with some embodiments.

DETAILED DESCRIPTION

[0027] In the following description, numerous specific details are set forth in order to provide a thorough understanding of the present disclosure. It will be apparent, however, to one skilled in the art that embodiments of the present disclosure may be practiced without some or all of these specific details. In other instances, well known process operations have not been described in detail in order not to unnecessarily obscure the present disclosure.

[0028] In the semiconductor industry, semiconductor substrates can undergo fabrication operations in various types of plasma chambers, such as capacitively coupled plasma (CCP) processing chambers and inductively coupled plasma (ICP) plasma processing chambers. In both CCP and ICP processing chambers, radiofrequency (RF) power is used to energize a process gas to transform the process gas into a plasma within a plasma processing region to which the substrate is exposed. Reactive species and/or charged species within the plasma interact with the substrate to modify a condition of the substrate, such as by modifying a material present on the substrate, or by depositing material on the substrate, or by removing/etching material from the substrate, by way of example. The CCP and ICP processing chambers are equipped with one or more electrodes and/or antenna that receive RF power for generating the plasma within the plasma processing region. Also, the CCP and ICP processing chambers are equipped with one or more electrodes that receive RF power and/or direct current (DC) power to generate a bias voltage at the substrate location for attracting charged species from the plasma toward the substrate.

[0029] FIG. **1** shows an RF signal supply system **100** that includes a low frequency RF signal generator **101** and a high frequency RF signal generator **102**, in accordance with some embodiments. Each of the low frequency RF signal generator **101** and the high frequency RF signal generator **102** is connected to supply RF signals through an impedance matching system **115** to plasma processing system **150**. In various embodiments, the plasma processing system **150** is either a CCP processing system or an ICP processing system. In various embodiments, the RF signal supply system **100** is connected through the impedance matching system **115** to an electrode or antenna (coil) within the plasma processing system **150**.

[0030] The low frequency RF signal generator **101** is configured to generate and transmit low frequency RF signals of controlled amplitude and frequency from an output **110** of the low frequency RF signal generator **101**, through/along an electrical conductor **113**, to an input **117** of the impedance matching system **115**. The low frequency RF signals then travel from an output **123** of the impedance matching system **115**, through/along the RF feed structure **160**, to an electrode or antenna within the plasma processing system **150**.

[0031] Similarly, the high frequency RF signal generator **102** is configured to generate and transmit high frequency RF signals of controlled amplitude and frequency from an output **171** of the high frequency RF signal generator **102**, through/along an electrical conductor **173**, to an input **175** of the impedance matching system **115**. The high frequency RF signals then travel from the output **123** of the impedance matching system **115**, through/along the RF feed structure **160**, to an electrode or antenna within the plasma processing system **150**.

[0032] The impedance matching system **115** includes a combination of capacitors and inductors configured and connected in an electrical circuit to match an impedance at the output **110** of the low frequency RF signal generator **101** to a design impedance (usually 50 Ohms). The impedance matching system **115** also includes a combination of capacitors and inductors configured and connected in an electrical circuit to match an impedance at the output **171** of the high frequency RF signal generator **102** to a design impedance (usually 50 Ohms). The impedance matching system **115** also includes a network interface controller (NIC) **139** that enables the impedance matching system **115** to send data to and receive data from systems outside of the impedance matching system **115**. Examples of the NIC **139** include a network interface card, a network adapter, etc. In various embodiments, the NIC **139** is configured to operate in accordance with one or more network communication protocols and associate physical layers, such as Ethernet and/or EtherCAT, among others.

[0033] The low frequency RF signal generator **101** includes an oscillator **103** for generating RF signals. The oscillator **103** is an electronic circuit that produces a periodic oscillating electrical signal, such a sine wave electrical signal, having a specified frequency within the RF range. In some embodiments, the oscillator **103** is a low-frequency oscillator capable of oscillating within a frequency range extending from about 50 kiloHertz (kHz) to about 3 megaHertz (MHz). In some embodiments, the oscillator **103** is set to generate low frequency RF signals within a frequency range extending from about 330 kHz to about 440 kHz. In some embodiments, the oscillator **103** is set to generate low frequency RF signals of about 400 KHz. An output of the oscillator **103** is connected to an input of a power amplifier **105**. The power amplifier **105** operates to amplify the low frequency RF signals generated by the oscillator **103**, and transmit the amplified low frequency RF signals through an output of the power amplifier **105** to the output **110** of the low frequency RF signal generator **101**.

[0034] The low frequency RF signal generator **101** also includes a control system **109** configured to provide for control of all operational aspects of the low frequency RF signal generator **101**. In some embodiments, the control system **109** includes a processor, a data storage device, an input/output interface, and a data bus through which the processor, the data storage device, and the input/output interface communicate data to and from each other. The control system **109** is connected to provide for control of the oscillator **103**, as indicated by connection **104**. The control system **109** is also connected to provide for control of the power amplifier **105**, as indicated by connection **106**. The control system **109** also includes a NIC **111** that enables the control system **109** to send data to and receive data from systems outside of the low frequency RF signal generator **101**. Examples of the NIC **111** include a network interface card, a network adapter, etc. In various embodiments, the NIC **111** is configured to operate in accordance with one or more network communication protocols and associate physical layers, such as Ethernet and/or EtherCAT, among others.

[0035] It should be understood that the control system **109** is connected and configured to control essentially any aspect of the low frequency RF signal generator **101**. And, it should be understood that the control system **109** can be connected and configured to monitor essentially any physical and/or electrical state, condition, and/or parameter at essentially any location within the low frequency RF signal generator **101**. The control system **109** is also configured to direct operation of the low frequency RF signal generator **101** in accordance with one or more prescribed algorithm(s). For example, the control system **109** is configured to operate the low frequency RF signal generator **101** by executing input and control instructions/programs. The input and control instructions/programs include a target RF power setpoint and a target frequency setpoint, among other parameters associated with operation and control of the low frequency RF signal generator **101**.

[0036] The low frequency RF signal generator **101** also includes a voltage/current (V/I) sensor **107** connected to the output **110** of the low frequency RF signal generator **101**. The V/I sensor **107** is connected to the control system **109**, as shown by connection **108**. In this configuration, the V/I sensor **107** provides a real-time measurement of voltage and current present on the output **110** of the low frequency RF signal generator **101** to the control system **109**. In some embodiments, the V/I sensor **107** is disposed within the low frequency RF signal generator **101**. The high frequency RF signal generator **102** includes an oscillator **177** for generating RF signals. The oscillator **177** is an electronic circuit that produces a periodic oscillating electrical signal, such a sine wave electrical signal, having a specified frequency within the RF range. In some embodiments, the oscillator **177** is a high-frequency oscillator capable of oscillating within a frequency range extending from about 10 MHz to about 130 MHz. In some embodiments, the oscillator **177** is set to generate high frequency RF signals within a range extending from about 57 MHz to about 63 MHz. In some embodiments, the oscillator **177** is set to generate high frequency RF signals of about 60 MHz. An output of the oscillator **177** is connected to an input of a power amplifier **179**. The power amplifier **179** operates to amplify the high frequency RF signals generated by the oscillator **177**, and transmit the amplified high frequency RF signals through an output of the power amplifier **179** to the output **171** of the high frequency RF signal generator **102**.

[0037] The high frequency RF signal generator **102** also includes a control system **181** configured to provide for control of all operational aspects of the high frequency RF signal generator **102**. In some embodiments, the control system **181** includes a processor, a data storage device, an input/output interface, and a data bus through which the processor, the data storage device, and the input/output interface communicate data to and from each other. The control system **181** is connected to provide for control of the oscillator **177**, as indicated by connection **178**. The control system **181** is also connected to provide for control of the power amplifier **179**, as indicated by connection **180**. The control system **181** also includes a NIC **183** that enables the control system **181** to send data to and receive data from systems outside of the high frequency RF signal generator **102**. Examples of the NIC **183** include a network interface card, a network adapter, etc. In various embodiments, the NIC **183** is configured to operate in accordance with one or more network communication protocols and associate physical layers, such as Ethernet and/or EtherCAT, among others.
[0038] It should be understood that the control system **181** is connected and configured to control essentially any aspect of the high frequency RF signal generator **102**. And, it should be understood that the control system **181** can be connected and configured to monitor essentially any physical and/or electrical state, condition, and/or parameter at essentially any location within the high frequency RF signal generator **102**. The control system **181** is also configured to direct operation of the high frequency RF signal generator **102** in accordance with a prescribed algorithm. For example, the control system **181** is configured to operate the high frequency RF signal generator **102** by executing input and control instructions/programs. The input and control instructions/programs include a target RF power setpoint and a target frequency setpoint, among other parameters associated with operation and control of the high frequency RF signal generator **102**.
[0039] The high frequency RF signal generator **102** also includes a voltage/current (V/I) sensor **185** connected to the output **171** of the high frequency RF signal generator **102**. The V/I sensor **185** is connected to the control system **181**, as shown by connection **182**. In this configuration, the V/I sensor **185** provides a real-time measurement of voltage and current present on the output **171** of the high frequency RF signal generator **102** to the control system **181**. In some embodiments, the V/I sensor **185** is disposed within the high frequency RF signal generator **102**.
[0040] In some embodiments, the control system **109** of the low frequency RF signal generator **101** is programmed to determine a real-time reflection coefficient (or Gamma (Γ)) at the output **110** of the low frequency RF signal generator **101**, where Γ=V.sub.r/V.sub.f, with V.sub.r being the complex amplitude of the reflected RF signal, and with V.sub.f being the complex amplitude of the forward RF signal. Also, in some embodiments, the control system **109** of the low frequency RF signal generator **101** is also programmed to determine a voltage standing wave ratio (VSWR) at the output **110** of the low frequency RF signal generator **101**, where VSWR=|V.sub.max|/|V.sub.min|=(1+|Γ|)/(1−|Γ|), with |V.sub.max|=|V.sub.f|+|V.sub.r| and |V.sub.min|=|V.sub.f|−|V.sub.r|. Minimization of the reflected RF power associated with the low frequency RF signal generated by the low frequency RF signal generator **101** occurs when the reflection coefficient at the output **110** of the low frequency RF signal generator **101** is as close to zero as possible. Also, minimization of the reflected RF power associated with the low frequency RF signal generated by the low frequency RF signal generator **101** occurs when the VSWR at the output **110** of the low frequency RF signal generator **101** is as close to one as possible, where one is the minimum possible value of VSWR. In some embodiments, the control system **109** is programmed to use the real-time measured voltage on the output **110** of the low frequency RF signal generator **101** to calculate the real-time reflection coefficient and/or VSWR at the output **110** of the low frequency RF signal generator **101**. The real-time reflection coefficient and/or VSWR at the output **110** of the low frequency RF signal generator **101**, as determined using voltage measurements taken within the low frequency RF signal generator **101**, can be used as a feedback signal to minimize the reflection

coefficient to as close to zero as possible and/or to minimize the VSWR to as close to one as possible.

[0041] Similarly, in some embodiments, the control system **181** of the high frequency RF signal generator **102** is programmed to determine the reflection coefficient (or Gamma (Γ)) and VSWR at the output **171** of the high frequency RF signal generator **102**. Minimization of the reflected RF power associated with the high frequency RF signal generated by the high frequency RF signal generator **102** occurs when the reflection coefficient at the output **171** of the high frequency RF signal generator **102** is as close to zero as possible. Also, minimization of the reflected RF power associated with the high frequency RF signal generated by the high frequency RF signal generator **102** occurs when the VSWR at the output **171** of the high frequency RF signal generator **102** is as close to one as possible, where one is the minimum possible value of VSWR. In some embodiments, the control system **181** is programmed to use the real-time measured voltage on the output **171** of the high frequency RF signal generator **102** to calculate the real-time reflection coefficient and/or VSWR at the output **171** of the high frequency RF signal generator **102**. The real-time reflection coefficient and/or VSWR at the output **171** of the high frequency RF signal generator **102**, as determined using voltage measurements taken within the high frequency RF signal generator **102**, can be used as a feedback signal to minimize the reflection coefficient to as close to zero as possible and/or to minimize the VSWR to as close to one as possible at the output **171** of the high frequency RF signal generator **102**. Also, the real-time reflection coefficient and/or VSWR at the output **171** of the high frequency RF signal generator **102**, as determined using voltage measurements taken within the high frequency RF signal generator **102**, can be used to determine a reflected RF power at the output of the **171** of the high frequency RF signal generator **102**.

[0042] A control module **163** of the plasma processing system **150** is connected to the control system **109** of the low frequency RF signal generator **101**, by way of a NIC **152** and the NIC **111**, as indicated by connection **143**. The control module **163** is connected to the control system **181** of the high frequency RF signal generator **102**, by way of the NIC **152** and the NIC **183**, as indicated by connection **144**. The control module **163** is connected to the impedance matching system **115**, by way of the NIC **152** and the NIC **139**, as indicated by connection **145**. The NIC **152** enables the control module **163** to send data to and receive data from systems outside of the control module **163**. Examples of the NIC **152** include a network interface card, a network adapter, etc. In various embodiments, the NIC **152** is configured to operate in accordance with one or more network communication protocols and associate physical layers, such as Ethernet and/or EtherCAT, among others.

[0043] In some embodiments, the control module **163** is programmed to direct operation of the low frequency RF signal generator **101** and the high frequency RF signal generator **102** in accordance with a frequency tuning process. The frequency tuning process automatically adjusts an operating frequency of the low frequency RF signal generator **101** about a target frequency of the low frequency signal to minimize reflected power at the output **110** of the low frequency RF signal generator **101**. Also, in the frequency tuning process, an operating frequency of the high frequency RF signal generator **102** is automatically adjusted about a target frequency of the high frequency signal to minimize reflected power at the output **171** of the high frequency RF signal generator **102**. In the frequency tuning process, the operating frequency of the high frequency RF signal generator **102** is separately adjusted about the target frequency of the high frequency signal in each of a plurality of temporal bins that collectively span a complete cycle of the low frequency signal generated by the low frequency RF signal generator **101**, with the plurality of temporal bins and corresponding separate operating frequency adjustments (of the high frequency RF signal generator **102**) repeating in sequence over each cycle of the low frequency signal generated by the low frequency RF signal generator **101**.

[0044] FIG. **2** shows a diagram of the frequency tuning process, in accordance with some embodiments. An upper plot **201** shows a curve **203** of voltage measured as a function of time at the output **110** of the low frequency RF signal generator **101**. The curve **203** represents the low frequency signal generated by the low frequency RF signal generator **101**. The low frequency signal is a sinusoidal signal characterized by a repeating cycle. In the upper plot **201**, a given cycle of the low frequency signal begins at a point P**1** and ends at a point P**3**, with a point P**2** marking the half-cycle location. In the example of FIG. **2**, the cycle of the low frequency signal begins at the point P**1** where the low frequency signal crosses the zero voltage level in the positive direction. This beginning location of the cycle of the low frequency signal is referred to herein as the positive direction zero voltage crossing of the low frequency signal. The half-cycle location occurs at the point P**2** where the low frequency signal crosses the zero voltage level in the negative direction. And, the cycle of the low frequency signal ends at the point P**3** where the low frequency signal again crosses the zero voltage level in the positive direction. The cycle of the low frequency signal is divided into a plurality of temporal bins B**1** through B(N), where N is the total number of temporal bins. The example of FIG. **2** shows the cycle of the low frequency signal is divided into 20 (N=20) temporal bins B**1** through B**20**. The first temporal bin B**1** of the plurality of temporal bins B**1** through B(N) begins at a positive direction zero voltage crossing of the complete cycle of the low frequency signal. The last temporal bin B(N) of the plurality of temporal bins B**1** through B(N) ends at the next positive direction zero voltage crossing of the complete cycle of the low frequency signal.

[0045] It should be understood that the **20** temporal bins (N=20) of FIG. **2** is shown by way of example. In other embodiments, the plurality of temporal bins B**1** through B(N) can have N set at either less than 20 or greater than 20. Also, the example of FIG. **2** shows that each of the plurality of temporal bins B**1** through B(N) covers an equal amount of time. However, in other embodiments, different ones of the plurality of temporal bins B**1** through B(N) can be defined to cover different amounts of time. For example, if a higher resolution of adjustment in the frequency of the high frequency signal, as generated by the high frequency RF signal generator **102**, is required along a particular portion of the cycle of the low frequency signal, as generated by the low frequency RF signal generator **101**, some of the plurality of temporal bins B**1** through B(N) along the particular portion of the cycle of the low frequency signal are respectively defined to cover a smaller amount of time.

[0046] FIG. **2** also includes a lower plot **205** that shows adjustments of the operating frequency of the high frequency RF signal generator **102** at each of the plurality of temporal bins B**1** through B**20** that collectively span the complete cycle of the low frequency signal generated by the low frequency RF signal generator **101**. The operating frequency of the high frequency RF signal generator **102** is set at an adjusted frequency during each of the plurality of temporal bins B**1** through B**20**. The adjusted operating frequency of the high frequency RF signal generator **102** in any given one of the plurality of temporal bins B**1** through B(N) is independently and separately set relative to others of the plurality of temporal bins B**1** through B(N). In some embodiments, the adjusted frequency of a given one of the plurality of temporal bins B**1** through B(N) is an integer multiple of a frequency adjustment amount (f.sub.adj) about a target frequency (HF0) of the high frequency signal generated by the high frequency RF signal generator **102**. For example, FIG. **2** shows a line corresponding to the target frequency (HF0) of the high frequency signal generated by the high frequency RF signal generator **102**. FIG. **2** also shows lines for each of the integer multiples of the frequency adjustment amount (f.sub.adj), respectively. As shown in FIG. **2**, the adjusted frequency of a given one of the plurality of temporal bins B**1** through B**20** is an integer multiple of the frequency adjustment amount (f.sub.adj) about the target frequency (HF0). In some embodiments, the integer multiple is either −4, −3, −2, −1, 0, +1, +2, +3, +4. However, in other embodiments, integer multiples less than −4 and/or greater than +4 can be used. Also, in some embodiments, the integer multiple is replaced by a fractional multiple. Also, in some embodiments, the frequency adjustment amount (f.sub.adj) is set as the target frequency of the low frequency

signal as generated by the low frequency RF signal generator **101**. In the example of FIG. **2**, if the target frequency of the low frequency signal as generated by the low frequency RF signal generator **101** is 400 kHz, then the bin-level operating frequency of the high frequency RF signal generator **102** at −4(f.sub.adj) is HF0−1600 kHz, and at −3 (f.sub.adj) is HF0−1200 kHz, an at −2 (f.sub.adj) is HF0−800 KHz, and at −1 (f.sub.adj) is HF0−400 kHz, and at 0 (f.sub.adj) is HF0, and at +1 (f.sub.adj) is HF0+400 KHz, and at +2 (f.sub.adj) is HF0+800 kHz, and at +3 (f.sub.adj) is HF0+1200 kHz, and at +4 (f.sub.adj) is HF0+1600 kHz. The operating frequency of the high frequency RF signal generator **102** for a given one the plurality of temporal bins B**1** through B(N), e.g., the setting of integer multiple of the frequency adjustment amount (f.sub.adj) for the given one of the plurality of temporal bins B**1** through B(N), is determined empirically as the frequency adjustment that minimizes the reflected RF power at the output **171** of the high frequency RF signal generator **102** during the given one of the plurality of temporal bins B**1** through B(N). Also, in some embodiments, the frequency adjustment amount (f.sub.adj) is set at a determined amount of frequency that is different than the target frequency of the low frequency signal as generated by the low frequency RF signal generator **101**.
[0047] The adjusted frequencies of the high frequency RF signal generator **102** across the plurality of temporal bins B**1** through B(N) are repeated for each cycle of the low frequency signal generated by the low frequency RF signal generator **101**. Periodically, the frequency tuning process will re-tune (re-determine) the adjusted frequencies of the high frequency RF signal generator **102** for the plurality of temporal bins B**1** through B(N) to ensure that the reflected RF power at the output **171** of the high frequency RF signal generator **102** is minimized to the extent possible. In some embodiments, the frequency tuning process is implemented by programming the control module **163**, which in turn directs operation of the control system **109** within the low frequency RF signal generator **101** and operation of the control system **181** within the high frequency RF signal generator **102**.
[0048] FIG. **3** shows various plots of normalized voltage and normalized current as a function of time as measured at the output **123** of the impedance matching system **115**, when the RF signal generation system **100** is operating in accordance with the frequency tuning process of FIG. **2**, in accordance with some embodiments. With reference back to FIG. **1**, a voltage/current (V/I) sensor **195** is connected to the output **123** of the impedance matching system **115**. The V/I sensor **195** is connected to the control module **163**, as shown by connection **196**. In this configuration, the V/I sensor **195** provides a real-time measurement of voltage and current present at the output **123** of the impedance matching system **115** to the control module **163**. The various plots shown in FIG. **3** correspond to voltage measurements or current measurements taken by the V/sensor **195** at the output **123** of the impedance matching system **115**.
[0049] FIG. **3** includes an upper plot **301** that shows normalized voltage as a function of time as measured at the output **123** of the impedance matching system **115**, including normalized voltages associated with various harmonics of the low frequency RF signal generated by the low frequency RF signal generator **101**, in accordance with some embodiments. The upper plot **301** shows a curve **303** representing normalized voltage as a function of time at the output **123** of the impedance matching system **115** corresponding to the full bandwidth combination of low frequency RF signals associated with the low frequency RF signal generated by the low frequency RF signal generator **101**. The full bandwidth combination of low frequency RF signals includes the fundamental (base) low frequency RF signal generated by the low frequency RF signal generator **101** and all harmonic frequency signals associated with the fundamental (base) low frequency RF signal. The upper plot **301** also shows a curve **305** representing normalized voltage as a function of time at the output **123** of the impedance matching system **115** corresponding to just the fundamental (base) low frequency RF signal generated by the low frequency RF signal generator **101**. The upper plot **301** also shows a curve **307** representing normalized voltage as a function of time at the output **123** of the impedance matching system **115** corresponding to a second harmonic frequency of the fundamental

(base) low frequency RF signal generated by the low frequency RF signal generator **101**. It should be understood that the second harmonic of the fundamental (base) low frequency RF signal corresponding to the curve **307** is sourced downstream of the output **123** of the impedance matching system **115** and is not generated by the low frequency RF signal generator **101**. The upper plot **301** also shows a curve **309** representing normalized voltage as a function of time at the output **123** of the impedance matching system **115** corresponding to third and higher harmonic frequencies of the fundamental (base) low frequency RF signal generated by the low frequency RF signal generator **101**. It should be understood that the third and higher harmonic frequencies of the fundamental (base) low frequency RF signal corresponding to the curve **309** are sourced downstream of the output **123** of the impedance matching system **115** and are not generated by the low frequency RF signal generator **101**.

[0050] FIG. **3** also includes a lower plot **311** that shows normalized current as a function of time as measured at the output **123** of the impedance matching system **115** for the high frequency RF signal generated by the high frequency RF signal generator **102** and for various harmonic frequencies of the high frequency RF signal, in accordance with some embodiments. For reference, the lower plot **311** includes a subplot **313** that shows the curve **303** (as shown in the upper plot **301**) corresponding to the full bandwidth combination of low frequency RF signals associated with the low frequency RF signal generated by the low frequency RF signal generator **101**. The lower plot **311** includes a subplot **315** that shows a curve **316** representing normalized current as a function of time at the output **123** of the impedance matching system **115** corresponding to the full bandwidth combination of high frequency RF signals associated with the high frequency RF signal generated by the high frequency RF signal generator **102**. The full bandwidth combination of high frequency RF signals includes the fundamental (base) high frequency RF signal generated by the high frequency RF signal generator **102** and all harmonic frequency signals associated with the fundamental (base) high frequency RF signal. In the example of FIG. **3**, the high frequency RF signals have a fundamental (base) frequency of 60 MHz and the low frequency RF signals have a fundamental (base) frequency of 400 KHz. Therefore, the curve **316** of the normalized current corresponding to the high frequency RF signals cycles about 150 times faster that the curve **303** of the voltage corresponding to the low frequency RF signals. So, on a single-cycle scale of the low frequency RF signal curve **303**, the high frequency RF signal curve **316** traces out a substantially solid region, as shown in FIG. **3**.

[0051] The lower plot **311** also includes a subplot **317** that shows a curve **318** representing normalized current as a function of time at the output **123** of the impedance matching system **115** corresponding to just the fundamental (base) high frequency RF signal generated by the high frequency RF signal generator **102**. The lower plot **311** also includes a subplot **319** that shows a curve **320** representing normalized current as a function of time at the output **123** of the impedance matching system **115** corresponding to a second harmonic frequency of the fundamental (base) high frequency RF signal generated by the high frequency RF signal generator **101**. It should be understood that the second harmonic of the fundamental (base) high frequency RF signal corresponding to the curve **320** is sourced downstream of the output **123** of the impedance matching system **115** and is not generated by the high frequency RF signal generator **102**. The lower plot **311** also includes a subplot **321** that shows a curve **322** representing normalized current as a function of time at the output **123** of the impedance matching system **115** corresponding to a third harmonic frequency of the fundamental (base) high frequency RF signal generated by the high frequency RF signal generator **101**. It should be understood that the third harmonic of the fundamental (base) high frequency RF signal corresponding to the curve **322** is sourced downstream of the output **123** of the impedance matching system **115** and is not generated by the high frequency RF signal generator **102**.

[0052] The lower plot **311** also includes a subplot **323** that shows a curve **324** representing normalized current as a function of time at the output **123** of the impedance matching system **115** corresponding to a fourth harmonic frequency of the fundamental (base) high frequency RF signal generated by the high frequency RF signal generator **101**. It should be understood that the fourth harmonic of the fundamental (base) high frequency RF signal corresponding to the curve **324** is sourced downstream of the output **123** of the impedance matching system **115** and is not generated by the high frequency RF signal generator **102**. The lower plot **311** also includes a subplot **325** that shows a curve **326** representing normalized current as a function of time at the output **123** of the impedance matching system **115** corresponding to a fifth harmonic frequency of the fundamental (base) high frequency RF signal generated by the high frequency RF signal generator **101**. It should be understood that the fifth harmonic of the fundamental (base) high frequency RF signal corresponding to the curve **326** is sourced downstream of the output **123** of the impedance matching system **115** and is not generated by the high frequency RF signal generator **102**. The lower plot **311** also includes a subplot **327** that shows a curve **328** representing normalized current as a function of time at the output **123** of the impedance matching system **115** corresponding to a sixth harmonic frequency of the fundamental (base) high frequency RF signal generated by the high frequency RF signal generator **101**. It should be understood that the sixth harmonic of the fundamental (base) high frequency RF signal corresponding to the curve **328** is sourced downstream of the output **123** of the impedance matching system **115** and is not generated by the high frequency RF signal generator **102**.

[0053] The curve **303** in the upper plot **301** (and in the subplot **313**) shows that the normalized voltage as a function of time at the output **123** of the impedance matching system **115** corresponding to the full bandwidth combination of low frequency RF signals associated with the low frequency RF signal generated by the low frequency RF signal generator **101** exhibits a deviation in slope within a temporal region **310** as the voltage approaches the zero voltage level in the positive direction. The deviation in slope of the curve **303** within the temporal region **310** is caused by increase in plasma density caused by secondary electrons generated by ions at the substrate. The maximum flux of electrons and maximum of plasma density is delayed from maximum sheath voltage (Point A) due to ion inertia. Also, the deviation in slope of the curve **303** within the temporal region **310** occurs in conjunction with higher amplitudes of the higher order harmonic frequency signals associated with the fundamental (base) low frequency RF signal as generated by the low frequency RF signal generator **101**.

[0054] Additionally, the higher order harmonic signals associated with the fundamental (base) high frequency RF signal generated by the high frequency RF signal generator **102**, such as shown in subplots **319**, **321**, **323**, **325**, and **327**, are not uniformly distributed throughout a given cycle of the low frequency RF signal generated by the low frequency RF signal generator **101**. FIG. **3** shows that the deviation in slope of the voltage curve **303** within the temporal region **310** is correlated to higher amplitudes of higher order harmonic signals associated with the fundamental (base) high frequency RF signal generated by the high frequency RF signal generator **102**. For example, the lower plot **311** shows an outline of the temporal region **310** across the subplots **315**, **317**, **319**, **321**, **323**, **325**, and **327**. As shown within the temporal region **310** within subplots **319**, **321**, **323**, **325**, and **327**, the normalized current associated with the higher order harmonics of the fundamental (base) high frequency RF signal is substantially increased at the onset of the plasma density increase due to the secondary electrons and is sustained through the duration of the plasma sheath collapse. Also, as shown within the temporal region **310** within the subplot **317**, the normalized current corresponding to the fundamental (base) frequency of the high frequency RF signal drops significantly and rapidly at the onset of the plasma sheath collapse at the substrate level.

[0055] The plasma sheath potential is equal to a difference between the RF voltage applied to the plasma and a measured plasma potential. A standing wave in the plasma sheath potential occurs for a short period of time within the temporal window **310** at or near the onset of plasma sheath collapse. It is considered that the standing wave in the plasma sheath potential is attributed to occurrence of the higher order harmonics of the fundamental (base) high frequency RF signal.

Also, the standing wave in the plasma sheath potential is considered to be responsible for non-uniformity in plasma process results across the substrate. For example, in plasma etching processes, the standing wave in plasma sheath potential is considered to be a contributing factor to center-to-middle (C/M) etch rate non-uniformity across the substrate, where center refers a center of a circular-shaped substrate and middle refers to a mid-radial location between the center and a peripheral edge of the circular-shaped substrate. In some high aspect ratio (HAR) etching applications, the C/M etch rate non-uniformity across the substrate is a global tilt problem related to offset in bottom critical dimension (BCD) of HAR features formed across the substrate. M ore specifically, ions that reach the bottom of the HAR structures are high energy ions. Therefore, to effectively etch HAR features, it is necessary to have high energy ions leave the plasma sheath and travel down to the etch front at the bottom of the HAR features. Because the high energy ions leave the plasma sheath at or near the maximum sheath potential, as driven by the low frequency RF signal generated by the low frequency RF signal generator **101**, perturbations in the sheath potential (such as the aforementioned standing wave in the sheath potential) affect the production and distribution of high energy ions across the substrate and in turn manifest as C/M etch rate non-uniformity, and in particular as a form of C/M etch rate non-uniformity that adversely affects formation of HAR features within a central region of the substrate as compared to the mid-radial region of the substrate. When integrated over time, the standing wave in the sheath potential that occurs at or near the onset of the plasma sheath collapse during each cycle of the low frequency RF signal causes less overall etching to occur near the central region of the substrate as compared to near the mid-radial region of the substrate.

[0056] Also, the deviation in slope of the voltage curve **303** within the temporal region **310** is non-advantageous because the deviation in slope extends the duration over which the plasma sheath voltage is low enough to allow for collapse of the plasma sheath at the substrate level. In other words, it is more advantageous for the temporal region **310** to have a shorter duration in order to reduce the duration of plasma sheath collapse in a given cycle of the low frequency RF signal as generated by the low frequency RF signal generator **101**.

[0057] Systems and methods are disclosed herein for mitigating the impact on C/M etch rate non-uniformity caused by plasma sheath collapse during each cycle of the low frequency RF signal as generated by the low frequency RF signal generator **101**, when operating in accordance with the frequency tuning process of FIG. **2**. The plasma sheath potential responds to the low frequency RF signal more than to the high frequency RF signal because the low frequency RF signal is much higher voltage that the high frequency RF signal. For example, in some implementations of the frequency tuning process of FIG. **2**, the low frequency RF signal has a peak voltage of about 5 kiloVolts (kV), and the high frequency RF signal has a peak voltage of about 300 volts (V) to about 500 V. Therefore, the plasma sheath potential is driven by the low frequency RF signal, whereas the plasma density is driven by the high frequency RF signal. Therefore, the low frequency RF signal is more effective than the high frequency RF signal for tuning the plasma sheath impedance. Also, because of the significant difference in voltage between the low frequency RF signal and the high frequency RF signal, it is not practical to significantly change the plasma sheath voltage by changing the high frequency RF signal. When the plasma sheath potential collapses within a given cycle of the low frequency RF signal due to low voltage, it is possible to get different shapes for the plasma sheath voltage waveform as a function of time by changing the phase and/or voltage of higher order harmonic frequency signals associated with the fundamental (base) low frequency RF signal as generated by the low frequency RF signal generator **101**. Because modification of the higher order harmonic frequency signals associated with the fundamental (base) low frequency RF signal causes modification of the plasma sheath potential, it is possible to use the higher order harmonic frequency signals associated with the fundamental (base) low frequency RF signal to control the plasma sheath potential and corresponding coupling of the high frequency RF signal to the plasma.

[0058] When operating in accordance with the frequency tuning process of FIG. **2**, by manipulating the phase and/or voltage of higher order harmonic frequency signals associated with the fundamental (base) low frequency RF signal, it is possible to change the shape of the waveform of the full bandwidth low frequency RF signal voltage as a function of time, so as to cause an increase in integrated plasma sheath voltage over time, which will in turn provide for an improvement of plasma process result uniformity across the substrate, e.g., provide for a reduction in C/M etch rate non-uniformity. Also, by changing the shape of the waveform of the full bandwidth low frequency RF signal voltage as a function of time, it is possible to correspondingly change the coupling of the high frequency RF signal to the plasma as a function of time.

[0059] In some embodiments, when operating in accordance with the frequency tuning process of FIG. **2**, one or more higher order harmonic frequency signals associated with the fundamental (base) low frequency RF signal are introduced (supplied to the plasma) with respective phase shifts and voltages set so as to interfere with signals generated within the plasma that have the same harmonic frequency. This interference caused by the introduced harmonic frequency signals serves to negate and/or reduce the impact that the plasma-generated signals of corresponding harmonic frequency have on the deviation in the slope of the full bandwidth low frequency RF signal curve **303** within the temporal region **310**, as shown in FIG. **3**, which in turn serves to reduce the non-uniformity in plasma process results across the substrate due to the integrated effect of the collapse of the plasma sheath potential in each cycle of the low frequency RF signal.

[0060] In some embodiments, when operating in accordance with the frequency tuning process of FIG. **2**, the waveform of the full bandwidth low frequency RF signal is generated to have a non-sinusoidal shape so that plasma sheath collapse duration within each cycle of the low frequency RF signal is reduced. The reduction in plasma sheath collapse duration within each cycle of the low frequency RF signal serves to change the fraction of low frequency RF signal cycle time in which harmonic frequencies of the fundamental (base) low frequency signal are generated by the plasma, which in turn changes the amount of time in which standing waves are generated in the plasma sheath potential, which in turn changes the amount of time in which high energy ions are non-uniformly distributed across the substrate. The reduction in plasma sheath collapse duration within each cycle of the low frequency RF signal will have an even greater impact on reducing plasma process result non-uniformity across the substrate as the fundamental (base) frequency of the low frequency RF signal is reduced, such as reduced from about 400 kHz to about 50 kHz, with a corresponding increase in the overall duration of each cycle of the fundamental (base) low frequency RF signal.

[0061] FIG. **4** shows an example of injecting higher order harmonic frequency signals in conjunction with the fundamental (base) frequency signal to generate a non-sinusoidal waveform shape, in accordance with some embodiments. In FIG. **4**, the fundamental (base) frequency signal has a waveform that is represented by the curve **401**, which has a sinusoidal shape. The third harmonic frequency signal and the fifth harmonic frequency signal of the fundamental (base) frequency are combined with the fundamental (base) frequency signal to generate a waveform represented by the curve **403**, which has a square shape. If it is considered that the waveforms corresponding to the curve **401** and the curve **403** represent different waveforms of the full bandwidth low frequency RF signal generated in accordance with the frequency tuning process of FIG. **2**, FIG. **4** demonstrates how use of the square-shaped waveform for the full bandwidth low frequency RF signal can serve to reduce the plasma sheath potential collapse time and increase the time of the low voltage plasma sheath per cycle as compared to use of the sinusoidal waveform for the full bandwidth low frequency RF signal. Specifically, based on the observed temporal region **310** in FIG. **3** in which the plasma sheath collapse occurs, the sinusoidal-shaped curve **401** is shown to have an estimated sheath collapse duration **405**. And, the square-shaped curve **403** is shown to have an estimated sheath collapse duration **407**. It is clearly evident that the estimated sheath collapse duration **407** of the square-shaped curve **403** is less than the estimated sheath collapse duration **405** of the sinusoidal curve **401**. Therefore, waveform shaping of the full bandwidth low frequency RF signal can be achieved by combining higher order harmonic frequency signals of the fundamental (base) frequency signal with the fundamental (base) frequency signal in order to reduce the sheath collapse duration per cycle of the full bandwidth low frequency RF signal.

[0062] In some embodiments, when operating in accordance with the frequency tuning process of FIG. **2**, the waveform of the full bandwidth low frequency RF signal is generated such that a negative half of each cycle of the full bandwidth low frequency RF signal has a longer duration than a positive half of each cycle of the full bandwidth low frequency RF signal. The plasma sheath potential is greatest during the negative half of each cycle of the full bandwidth low frequency RF signal. Therefore, if the waveform of the full bandwidth low frequency RF signal is configured to spend more time in the negative half of the cycle than in the positive half of the cycle, the plasma sheath potential will be greater over a larger amount of time. Also, with the plasma sheath potential being greater over a larger amount of time, the harmonic frequencies of the fundamental (base) high frequency RF signal will have less overall adverse effect on the plasma sheath potential and correspondingly less adverse effect on the plasma process result uniformity across the substrate.

[0063] FIGS. **5**A, **5**B, and **5**C collectively show examples of how higher order harmonic frequency signals can be combined with the fundamental (base) frequency signal to generate a non-sinusoidal cyclical waveform shape in which a negative half of each cycle is longer that a positive half of each cycle, in accordance with some embodiments. FIG. **5**A shows a composite signal waveform **501** that is a combination of a fundamental (base) frequency signal and a third harmonic frequency signal of the fundamental (base) frequency signal and a fifth harmonic frequency signal of the fundamental (base) frequency signal, in accordance with some embodiments. FIG. **5**A also shows an ideal square wave signal waveform **502** for reference. Comparison of the composite signal waveform **501** with the ideal square wave signal waveform **502** shows that combination of the fundamental (base) frequency signal with the corresponding signals having the third and fifth harmonic frequencies of the fundamental (base) frequency results in the composite signal waveform **501** having an approximated square wave shape. In the example of FIG. **5**A, each of the fundamental (base) frequency signal, the third harmonic frequency signal of the fundamental (base) frequency signal, and the fifth harmonic frequency signal of the fundamental (base) frequency signal are aligned in phase with each other and have substantially equal amplitudes. The negative half of a given cycle of the composite signal waveform **501** has a duration D.sub.NH-135. The positive half of the given cycle of the composite signal waveform **501** has a duration D.sub.PH-135. In the composite signal waveform **501**, the duration D.sub.NH-135 of the negative half of the cycle is equal to the duration D.sub.PH-135 of the positive half of the cycle. Therefore, a composite signal waveform, such as the waveform **501**, formed by combining the fundamental (base) frequency signal with both a phase-aligned third harmonic frequency signal of the fundamental (base) frequency signal and a phase-aligned fifth harmonic frequency signal of the fundamental (base) frequency signal has a cycle defined by a negative half-cycle and a positive half-cycle of equal duration.

[0064] Particular harmonic frequency signals can be combined with the fundamental (base) frequency signal to generate a composite signal waveform that has a cycle defined by a negative half-cycle and a positive half-cycle of different duration. FIG. **5**B shows a composite signal waveform **503** that is a combination of a fundamental (base) frequency signal and a second harmonic frequency signal of the fundamental (base) frequency signal and a fourth harmonic frequency signal of the fundamental (base) frequency signal, in accordance with some embodiments. FIG. **5**B also shows an ideal square wave signal waveform **504** for reference. Comparison of the composite signal waveform **503** with the ideal square wave signal waveform **504** shows that combination of the fundamental (base) frequency signal with the corresponding signals having the second and fourth harmonic frequencies of the fundamental (base) frequency results in the composite signal waveform **503** having an approximated square wave shape. In the example of FIG. **5**B, each of the fundamental (base) frequency signal, the second harmonic frequency signal of the fundamental (base) frequency signal, and the fourth harmonic frequency signal of the fundamental (base) frequency signal are aligned in phase with each other and have substantially equal amplitudes. The negative half of a given cycle of the composite signal waveform **503** has a duration D.sub.NH-124. The positive half of the given cycle of the composite signal waveform **503** has a duration D.sub.PH-124. In the composite signal waveform **503**, the duration D.sub.NH-124 of the negative half of the cycle is greater than the duration D.sub.PH-124 of the positive half of the cycle. Therefore, a composite signal waveform, such as the waveform **503**, formed by combining the fundamental (base) frequency signal with both a phase-aligned second harmonic frequency signal of the fundamental (base) frequency signal and a phase-aligned fourth harmonic frequency signal of the fundamental (base) frequency signal has a cycle in which the negative half-cycle has greater duration than the positive half-cycle.

[0065] FIG. **5**C shows a composite signal waveform **505** that is a combination of a fundamental (base) frequency signal and a second harmonic frequency signal of the fundamental (base) frequency signal and a third harmonic frequency signal of the fundamental (base) frequency signal, in accordance with some embodiments. FIG. **5**C also shows an ideal square wave signal waveform **506** for reference. Comparison of the composite signal waveform **505** with the ideal square wave signal waveform **506** shows that combination of the fundamental (base) frequency signal with the corresponding signals having the second and third harmonic frequencies of the fundamental (base) frequency results in the composite signal waveform **505** having an approximated square wave shape. In the example of FIG. **5**C, each of the fundamental (base) frequency signal, the second harmonic frequency signal of the fundamental (base) frequency signal, and the third harmonic frequency signal of the fundamental (base) frequency signal are aligned in phase with each other and have substantially equal amplitudes. The negative half of a given cycle of the composite signal waveform **505** has a duration D.sub.NH-123. The positive half of the given cycle of the composite signal waveform **505** has a duration D.sub.PH-123. In the composite signal waveform **505**, the duration D.sub.NH-123 of the negative half of the cycle is greater than the duration D.sub.PH-123 of the positive half of the cycle. Therefore, a composite signal waveform, such as the waveform **505**, formed by combining the fundamental (base) frequency signal with both a phase-aligned second harmonic frequency signal of the fundamental (base) frequency signal and a phase-aligned third harmonic frequency signal of the fundamental (base) frequency signal has a cycle in which the negative half-cycle has greater duration than the positive half-cycle. Also, the duration D.sub.NH-123 of the negative half of the cycle of the composite signal waveform **505** is greater than the duration D.sub.NH-124 of the negative half of the cycle of the composite signal waveform **503** of FIG. **5**B. As shown in FIGS. **5**A, **5**B, and **5**C, different harmonic frequency signals can be combined with a fundament (base) frequency signal to generate composite waveforms of different shape, particular with regard to the duration of the negative half-cycle relative to the duration of the positive half-cycle within the composite waveforms.

[0066] FIGS. **6**, **7**, and **8** collectively show examples of how higher order harmonic frequency signals of the fundamental (base) low frequency RF signal can be generated and combined with the fundamental (base) low frequency RF signal to generate a non-sinusoidal cyclical waveforms for the full bandwidth low frequency RF signal, when operating in accordance with the frequency tuning process of FIG. **2**, in accordance with some embodiments. FIG. **6** shows a reference low frequency RF signal **602** of sinusoidal shape, along with its harmonic frequency signal components, in accordance with some embodiments. FIG. **6** includes a subplot **601** that shows a full bandwidth version of the reference low frequency RF signal **602** used in the frequency tuning process of FIG. **2**, in accordance with some embodiments. A subplot **603** shows a fundamental (base) frequency component signal **602**A of the full bandwidth version of the reference low frequency RF signal **602**. A subplot **605** shows a component signal **602**B that includes second and third harmonic frequencies of the full bandwidth version of the reference low frequency RF signal **602**. A subplot **607** shows a component signal **602**C that includes fourth, fifth, and sixth harmonic frequencies of the full bandwidth version of the reference low frequency RF signal **602**. A subplot **609** shows a component signal **602**D that includes seventh and higher harmonic frequencies of the full bandwidth version of the reference low frequency RF signal **602**. Also, for reference, FIG. **6** shows a line **604** corresponding to the time at which the collapse of the sheath potential occurs, which corresponds to the temporal region **310** in which the deviation in slope of the curve **303** occurs in FIG. **3**.

[0067] FIG. **7** shows a composite low frequency RF signal **702** of substantially square shape formed by combining phase-aligned third and fifth harmonic frequency signals with a fundamental (base) frequency signal, in accordance with some embodiments. FIG. **7** includes a subplot **701** that shows a full bandwidth version of the composite low frequency RF signal **702** used in the frequency tuning process of FIG. **2**, in accordance with some embodiments. The composite low frequency RF signal **702** is formed by combining a fundamental (base) frequency signal of 400 kHz with both the third harmonic frequency signal of 1.2 MHz and the fifth harmonic frequency signal of 2 MHz. The total power of the composite low frequency RF signal **702** is distributed as 80% coming from the fundamental (base) frequency signal of 400 kHz, 15% coming from the third harmonic frequency signal of 1.2 MHz, and 5% coming from the fifth harmonic frequency signal of 2 MHz. A subplot **703** shows a fundamental (base) frequency component signal **702**A of the full bandwidth version of the composite low frequency RF signal **702**. A subplot **705** shows a component signal **702**B that includes second and third harmonic frequencies of the full bandwidth version of the composite low frequency RF signal **702**. A subplot **707** shows a component signal **702**C that includes fourth, fifth, and sixth harmonic frequencies of the full bandwidth version of the composite low frequency RF signal **702**. A subplot **709** shows a component signal **702**D that includes seventh and higher harmonic frequencies of the full bandwidth version of the composite low frequency RF signal **702**. Also, for reference, FIG. **7** shows a line **704** corresponding to the time at which the collapse of the sheath potential occurs, which corresponds to the temporal region **310** in which the deviation in slope of the curve **303** occurs in FIG. **3**.

[0068] FIG. **8** shows a composite low frequency RF signal **802** of sloped-square shape formed by combining phase-shifted third and fifth harmonic frequency signals with a fundamental (base) frequency signal, in accordance with some embodiments. FIG. **8** includes a subplot **801** that shows a full bandwidth version of the composite low frequency RF signal **802** used in the frequency tuning process of FIG. **2**, in accordance with some embodiments. The composite low frequency RF signal **802** is formed by combining a fundamental (base) frequency signal of 400 kHz with both the third harmonic frequency signal of 1.2 MHz and the fifth harmonic frequency signal of 2 MHz, with each of the third harmonic frequency signal and the fifth harmonic frequency signal shifted in phase by 30 degrees relative to the fundamental (base) frequency signal. The total power of the composite low frequency RF signal **802** is distributed as 80% coming from the fundamental (base) frequency signal of 400 kHz, 15% coming from the third harmonic frequency signal of 1.2 MHz, and 5% coming from the fifth harmonic frequency signal of 2 MHz. A subplot **803** shows a fundamental (base) frequency component signal **802**A of the full bandwidth version of the composite low frequency RF signal **802**. A subplot **805** shows a component signal **802**B that includes second and third harmonic frequencies of the full bandwidth version of the composite low frequency RF signal **802**. A subplot **807** shows a component signal **802**C that includes fourth, fifth, and sixth harmonic frequencies of the full bandwidth version of the composite low frequency RF signal **802**. A subplot **809** shows a component signal **802**D that includes seventh and higher harmonic frequencies of the full bandwidth version of the composite low frequency RF signal **802**. Also, for reference, FIG. **8** shows a line **804** corresponding to the time at which the collapse of the sheath potential occurs, which corresponds to the temporal region **310** in which the deviation in slope of the curve **303** occurs in FIG. **3**.

[0069] Each of the reference sinusoidal low frequency RF signal **602** of FIG. **6**, the composite square-shaped low frequency RF signal **702** of FIG. **7**, and the composite sloped-square-shaped low frequency RF signal **802** of FIG. **8** has a corresponding effect on the plasma sheath potential within the temporal region of the low frequency RF signal cycle, e.g., the temporal region **310**, in which plasma sheath potential collapses. Therefore, each of the reference sinusoidal low frequency RF signal **602** of FIG. **6**, the composite square-shaped low frequency RF signal **702** of FIG. **7**, and the composite sloped-square-shaped low frequency RF signal **802** of FIG. **8** has a corresponding effect on the uniformity of plasma process results across the substrate. FIG. **9** shows a plot of average film thickness versus radial position across the substrate obtained by performing etching processes in accordance with the frequency tuning process of FIG. **2**, with each etching process using a different one of the reference sinusoidal low frequency RF signal **602** of FIG. **6**, the composite square-shaped low frequency RF signal **702** of FIG. **7**, and the composite sloped-square-shaped low frequency RF signal **802** of FIG. **8**, in accordance with some embodiments. The data shown in FIG. **9** was obtained by subjecting a silicon substrate having a blanket silicon oxide film deposited thereon to a 60 second etching process in accordance with the frequency tuning process of FIG. **2**, in which the high frequency RF signal was applied at 60 MHz and 3.5 KW, and in which the low frequency RF signal was applied at 12.5 KW as either the reference sinusoidal low frequency RF signal **602** of FIG. **6**, the composite square-shaped low frequency RF signal **702** of FIG. **7**, or the composite sloped-square-shaped low frequency RF signal **802** of FIG. **8**. FIG. **9** demonstrates that the waveform shape of the low frequency RF signal used in the frequency tuning process of FIG. **2** has an effect on the uniformity of plasma process results across the substrate, such as on the center-to-middle etch rate uniformity.

[0070] As shown in the example of FIG. **8**, when higher order harmonic frequency signals of the fundamental (base) low frequency RF signal are generated and combined with the fundamental (base) low frequency RF signal to generate a composite cyclical waveform for the full bandwidth low frequency RF signal, the phase of the high order harmonic signals can be adjusted to obtain different waveform shapes. FIG. **10** shows various waveform shapes that are obtained by combining the third harmonic frequency signal and the fifth harmonic frequency signal with the fundamental (base) frequency signal, and by shifting the phase of the third and fifth harmonic frequency signals relative to the phase of the fundamental (base) frequency signal by various amounts, in accordance with some embodiments. FIG. **10** shows a sinusoidal reference signal **1001** corresponding to Equation 1. FIG. **10** also shows a square-shaped waveform signal **1003** corresponding to Equation 2, where A.sub.400 KHz is the relative power of the fundamental (base) frequency component, B.sub.1.2 MHz is the relative power of the third harmonic frequency component, and C.sub.2M Hz is the relative power of the fifth harmonic frequency component. FIG. **10** also shows sloped-square-shaped waveform signal **1005**A through **1005**F corresponding to Equation 3, where A.sub.400 kHz is the relative power of the fundamental (base) frequency component, B.sub.1.2 MHz is the relative power of the third harmonic frequency component, C.sub.2 MHz is the relative power of the fifth harmonic frequency component, and (Δϕ) is the shift in phase between the fundamental (base) frequency component and each of the third and fifth harmonic frequency components. Specifically, waveform signal **1005**A corresponds to a shift in phase (Δϕ) of 6 degrees. Waveform signal **1005**B corresponds to a shift in phase (Δϕ) of 9 degrees. Waveform signal **1005**C corresponds to a shift in phase (Δϕ) of 12 degrees. Waveform signal **1005**D corresponds to a shift in phase (A) of 15 degrees. Waveform signal **1005**E corresponds to a shift in phase (Δϕ) of 20 degrees. Waveform signal **1005**F corresponds to a shift in phase (Δϕ) of 30 degrees. In some embodiments, the sloped-square-shaped waveforms, such as **1005**A through **1005**F by way of example, can be utilized to compensate for charging during the low frequency RF signal cycle.

[00001] $Y = A_{400\mathrm{kHz}} \sin\varphi$ Equation1

$$Y = A_{400kHz}\sin(\varphi) + B_{1.2MHz}\sin(3\varphi) + C_{2MHz}\sin(5\varphi) \quad \text{Equation2}$$

$$Y = A_{400kHz}\sin(\varphi) + B_{1.2MHz}\sin(3\varphi - (360 - (3\Delta\varphi))) + C_{2MHz}\sin(5\varphi - (360 - (5\Delta\varphi))) \quad \text{Equation3}$$

[0071] FIG. **11** shows an RF signal supply system **1100** that includes the low frequency RF signal generator **101** and the high frequency RF signal generator **102**, as described with regard to FIG. **1**, and that further includes a plurality of harmonic frequency RF signal generators **1101-1** through **1101**-N, in accordance with some embodiments. In some embodiments, the number (N) of harmonic frequency RF signal generators is two (N=2). However, in other embodiments, the number (N) of harmonic frequency signal RF generators is greater than two (N>2). Each harmonic frequency RF signal generator **1101-1** through **1101**-N is set to generate an RF signal that is a particular harmonic frequency of the fundamental (base) low frequency RF signal generated by the low frequency RF signal generator **101**. The harmonic frequency RF signals generated by the harmonic frequency RF signal generators **1101-1** through **1101**-N are combined with the fundamental low frequency RF signal generated by the low frequency RF signal generator **101** in an impedance matching system **1115** to generate a composite low frequency RF signal waveform for use in the frequency tuning process of FIG. **2**, such as the composite low frequency RF signal waveforms **702** and **802** as described above with regard to FIGS. **7** and **8**, respectively.

[0072] Each of the harmonic frequency RF signal generators **1101-1** through **1101**-N is configured in a similar manner as the low frequency RF signal generator **101**. Each of the harmonic frequency RF signal generators **1101-1** through **1101**-N includes an oscillator **1103**-*x* for generating RF signals, where x is 1 to N. The oscillator **1103**-*x* is an electronic circuit that produces a periodic oscillating electrical signal, such a sine wave electrical signal, having a specified frequency within the RF range. The oscillator **1103**-*x* is capable of oscillating at a harmonic frequency of the operating frequency of the oscillator **103** of the low frequency RF signal generator **101**. An output of the oscillator **1103**-*x* is connected to an input of a power amplifier **1105**-*x*, where x is 1 to N. The power amplifier **1105**-*x* operates to amplify the RF signals generated by the oscillator **1103**-*x*, and transmit the amplified RF signals through an output of the power amplifier **1105**-*x* to the output **1110**-*x* of the harmonic frequency RF signal generator **1101**-*x*, where x is 1 to N.

[0073] Each harmonic frequency RF signal generator **1101**-*x* also includes a control system **1109**-*x*, where x is 1 to N, configured to provide for control of all operational aspects of the harmonic frequency RF signal generator **1101**-*x*. In some embodiments, the control system **1109**-*x* includes a processor, a data storage device, an input/output interface, and a data bus through which the processor, the data storage device, and the input/output interface communicate data to and from each other. The control system **1109**-*x* is connected to provide for control of the oscillator **1103**-*x*, as indicated by connection **1104**-*x*, where x is 1 to N. The control system **109** is also connected to provide for control of the power amplifier **1105**-*x*, as indicated by connection **1106**-*x*, where x is 1 to N. The control system **1109**-*x* also includes a NIC **1111**-*x*, where x is 1 to N, that enables the control system **1109**-*x* to send data to and receive data from systems outside of the harmonic frequency RF signal generator **1101**-*x*. Examples of the NIC **1111**-*x* include a network interface card, a network adapter, etc. In various embodiments, the NIC **1111**-*x* is configured to operate in accordance with one or more network communication protocols and associate physical layers, such as Ethernet and/or EtherCAT, among others. Also, the control module **163** of the plasma processing system **150** is connected to the control system **1109**-*x* of each harmonic frequency RF signal generator **1101**-*x*, by way of the NIC **152** and the NIC **1111**-*x*, as indicated by connection **1143**-*x*, where x is 1 to N.

[0074] It should be understood that the control system **1109**-*x* is connected and configured to control essentially any aspect of the harmonic frequency RF signal generator **1101**-*x*. And, it should be understood that the control system **1109**-*x* can be connected and configured to monitor essentially any physical and/or electrical state, condition, and/or parameter at essentially any location within the harmonic frequency RF signal generator **1101**-*x*. The control system **1109**-*x* is also configured to direct operation of the harmonic frequency RF signal generator **1101**-*x* in accordance with a prescribed algorithm. For example, the control system **1109**-*x* is configured to operate the harmonic frequency RF signal generator **1101**-*x* by executing input and control instructions/programs. The input and control instructions/programs include a target RF power setpoint and a target frequency setpoint, among other parameters associated with operation and control of the harmonic frequency RF signal generator **1101**-*x*. In some embodiments, the control system **1109**-*x* of each harmonic frequency RF signal generator **1101**-*x* is connected to the control system **109** of the low frequency RF signal generator **101**, such that the each harmonic frequency RF signal generator **1101**-*x* operates as a slave system to the low frequency RF signal generator **101**, which operates as a master system.

[0075] The harmonic frequency RF signal generator **1101**-*x* also includes a voltage/current (V/I) sensor **1107**-*x*, where x is 1 to N, connected to the output **1110**-*x* of the harmonic frequency RF signal generator **1101**-*x*. The V/I sensor **1107**-*x* is connected to the control system **1109**-*x*, as shown by connection **1108**-*x*, where x is 1 to N. In this configuration, the V/I sensor **1107**-*x* provides a real-time measurement of voltage and current present on the output **1110**-*x* of the harmonic frequency RF signal generator **1101**-*x* to the control system **1109**-*x*. In some embodiments, the V/I sensor **1107**-*x* is disposed within the harmonic frequency RF signal generator **1101**-*x*.

[0076] Each harmonic frequency RF signal generator **1101**-*x* is configured to generate and transmit harmonic frequency RF signals of controlled amplitude and frequency from the output **1110**-*x* of the harmonic frequency RF signal generator **1101**-*x*, through/along a corresponding electrical conductor **1113**-*x*, to a corresponding input **1117**-*x* of the impedance matching system **1115**, where x is 1 to N. The impedance matching system combines the harmonic frequency RF signals generated by the harmonic frequency RF signal generators **1101**-*x* with the fundamental low frequency RF signal generated by the low frequency RF signal generator **101** to generate the composite low frequency RF signal waveform, which travels from the output **123** of the impedance matching system **115**, through/along the RF feed structure **160**, to the electrode or antenna within the plasma processing system **150**.

[0077] FIG. **12** shows an example configuration of the impedance matching system **1115**, in accordance with some embodiments. The input **117** through which the fundamental (base) frequency RF signal is transmitted from low frequency RF signal generator **101** is connected to an impedance control circuit **1202** that includes a capacitor **1201**, an inductor **1203**, an inductor **1205**, a capacitor **1207**, a capacitor **1211**, and a capacitor **1213**. The input **117** is connected to a first terminal of the capacitor **1201**. A second terminal of the capacitor **1201** is connected to a first terminal of the inductor **1203**. A second terminal of the inductor **1203** is connected to a first terminal of the inductor **1205**. A second terminal of the inductor **1205** is connected to a pre-output node **1204**. Also, a first terminal of the capacitor **1207** is connected to both the second terminal of the capacitor **1201** and the first terminal of the inductor **1203**. A second terminal of the capacitor **1207** is connected to a reference ground potential **1209**. A first terminal of the capacitor **1211** is connected to both the second terminal of the inductor **1203** and the first terminal of the inductor **1205**. A second terminal of the capacitor **1211** is connected to the reference ground potential **1209**. A first terminal of the capacitor **1213** is connected to both the second terminal of the inductor **1205** and the pre-output node **1204**. A second terminal of the capacitor **1213** is connected to the reference ground potential **1209**.

[0078] The input **1117-1** through which the harmonic frequency RF signal is transmitted from harmonic frequency RF signal generator **1101-1** is connected to an impedance control circuit **1206-1** that includes a capacitor **1215-1**, an inductor **1217-1**, an inductor **1219-1**, a capacitor **1221-1**, a capacitor **1223-1**, and a capacitor **1225-1**. The input **1117-1** is connected to a first terminal of the capacitor **1215-1**. A second terminal of the capacitor **1215-1** is connected to a first terminal of the inductor **1217-1**. A second terminal of the inductor **1217-1** is connected to a first terminal of the inductor **1219-1**. A second terminal of the inductor **1219-1** is connected to the pre-output node

1204. Also, a first terminal of the capacitor **1221-1** is connected to both the second terminal of the capacitor **1215-1** and the first terminal of the inductor **1217-1**. A second terminal of the capacitor **1221-1** is connected to the reference ground potential **1209**. A first terminal of the capacitor **1223-1** is connected to both the second terminal of the inductor **1217-1** and the first terminal of the inductor **1219-1**. A second terminal of the capacitor **1223-1** is connected to the reference ground potential **1209**. A first terminal of the capacitor **1225-1** is connected to both the second terminal of the inductor **1219-1** and the pre-output node **1204**. A second terminal of the capacitor **1225-1** is connected to the reference ground potential **1209**.

[0079] In some embodiments, each input **1117-1** through **1117**-N of the impedance matching system **1115** through which a given harmonic frequency RF signal is transmitted from a corresponding harmonic frequency RF signal generator **1101-1** through **1101**-N is connected to a corresponding impedance control circuit **1206-1** through **1206**-N that is configured like the impedance control circuit **1206-1**. In this manner, the input **1117**-N through which the harmonic frequency RF signal is transmitted from Nth harmonic frequency RF signal generator **1101**-N is connected to an impedance control circuit **1206**-N that includes a capacitor **1215**-N, an inductor **1217**-N, an inductor **1219**-N, a capacitor **1221**-N, a capacitor **1223**-N, and a capacitor **1225**-N. The input **1117**-N is connected to a first terminal of the capacitor **1215**-N. A second terminal of the capacitor **1215**-N is connected to a first terminal of the inductor **1217**-N. A second terminal of the inductor **1217**-N is connected to a first terminal of the inductor **1219**-N. A second terminal of the inductor **1219**-N is connected to the pre-output node **1204**. Also, a first terminal of the capacitor **1221**-N is connected to both the second terminal of the capacitor **1215**-N and the first terminal of the inductor **1217**-N. A second terminal of the capacitor **1221**-N is connected to the reference ground potential **1209**. A first terminal of the capacitor **1223**-N is connected to both the second terminal of the inductor **1217**-N and the first terminal of the inductor **1219**-N. A second terminal of the capacitor **1223**-N is connected to the reference ground potential **1209**. A first terminal of the capacitor **1225**-N is connected to both the second terminal of the inductor **1219**-N and the pre-output node **1204**. A second terminal of the capacitor **1225**-N is connected to the reference ground potential **1209**.

[0080] The input **175** through which the high frequency RF signal is transmitted from high frequency RF signal generator **102** is connected to an impedance control circuit **1208** that includes a capacitor **1227**, an inductor **1229**, an inductor **1231**, and a capacitor **1233**. The input **175** is connected to a first terminal of the capacitor **1227**. A second terminal of the capacitor **1227** is connected to a first terminal of the inductor **1229**. A second terminal of the inductor **1229** is connected to a final-output node **1210**. Also, a first terminal of the inductor **1231** is connected to each of the input **175**, the first terminal of the capacitor **1227**, and first terminal of the capacitor **1233**. A second terminal of the inductor **1231** is connected to the reference ground potential **1209**. The first terminal of the capacitor **1233** is connected to each of the input **175**, the first terminal of the inductor **1231** and the first terminal of the capacitor **1227**. A second terminal of the capacitor **1233** is connected to the reference ground potential **1209**.

[0081] The pre-output node **1204** is connected to a first terminal of an output inductor **1235**. A second terminal of the output inductor **1235** is connected to the final-output node **1210**. The final-output node is connected to the output **123** of the impedance matching system **1115**, which is connected to the RF feed structure **160** of the plasma processing system **150**. In some embodiments, voltage and/or current measurements of the composite low frequency RF signal waveform are taken at the pre-output node **1204**. In these embodiments, the output inductor **1235** is provided to prevent the high frequency RF signals at the final-output node **1210** from interfering with the voltage and/or current measurements taken at the pre-output node **1204**. It should be understood that the configuration of the impedance matching system **1115** as shown in FIG. **12** is provided by way of example. In other embodiments, the impedance matching system **1115** can be configured in different ways, with different combinations of capacitors and inductors, so as to

ensure that impedance seen at the output **110** of the low frequency RF signal generator **101** is substantially close to a design basis operating impedance, and so that the impedances seen at each output **1110**-*x* of the harmonic frequency RF signal generators **1101**-*x* is substantially close to a design basis operating impedance, and so that the impedance seen at the output **171** of the high frequency RF signal generator **102** is substantially close to a design basis operating impedance.
[0082] Using the harmonic frequency RF signal generators **1101-1** through **1101**-N it is possible to manipulate the frequency and phase of the harmonic frequency RF signals that are combined with the fundamental (base) frequency RF signal to generate a particular composite low frequency RF signal waveform that serves to advantageously influence the portion of the plasma sheath where the plasma potential collapses so as to maintain and/or improve coupling of the high frequency RF signal to the plasma and thereby reduce corresponding plasma process result non-uniformity across the substrate. It should be understood that each of the harmonic frequency RF signal generators **1101-1** through **1101**-N can be independently controlled to enable control of both the phase difference and the voltage difference between each harmonic frequency RF signal and the fundamental (base) low frequency RF signal. Also, while the examples of FIGS. **7** and **8** demonstrate combination of the first (fundamental), third, and fifth harmonics to generate the composite low frequency RF signal waveform, it should be understood that in various embodiments essentially any combination of two or more harmonics can be combined with the first (fundamental) harmonic to generate a composite low frequency RF signal waveform having particular characteristics. In some embodiments, the composite low frequency RF signal waveform can be generated to provide for a higher plasma sheath potential than what is achievable from using a sinusoidal low frequency RF signal at a same power level.
[0083] As previously mentioned, in various embodiments, the plasma processing system **150** is either a CCP processing system or an ICP processing system. FIG. **13**A shows an example vertical cross-section diagram of a CCP processing system **150**A, in accordance with some embodiments of the present disclosure. The CCP processing system **150**A includes a chamber **1301** within which a plasma processing region **1302** exists. Within the plasma processing region **1302**, a plasma **1323** (represented by the dashed oval region) is generated in exposure to a substrate **1305** to affect a change to the substrate **1305** in a controlled manner. In various fabrication processes, the change to the substrate **1305** can be a change in material or surface condition on the substrate **1305**. For example, in various fabrication processes, the change to the substrate **1305** can include one or more of etching of a material from the substrate **1305**, deposition of a material on the substrate **1305**, or modification of material present on the substrate **1305**. In some embodiments, the substrate **1305** is a semiconductor wafer undergoing a fabrication procedure. However, it should be understood that in various embodiments, the substrate **1305** can be essentially any type of substrate that is subjected to a plasma-based fabrication process. For example, in some embodiments, the substrate **1305** as referred to herein can be a substrate formed of silicon, sapphire, GaN, GaAs or SiC, or other substrate materials, and can include glass panels/substrates, metal foils, metal sheets, polymer materials, or the like. Also, in various embodiments, the substrate **1305** as referred to herein may vary in form, shape, and/or size. For example, in some embodiments, the substrate **1305** referred to herein may correspond to a 200 mm (millimeters) diameter semiconductor wafer, a 300 mm diameter semiconductor wafer, or a 450 mm diameter semiconductor wafer, among other semiconductor wafer sizes. Also, in some embodiments, the substrate **1305** referred to herein may correspond to a non-circular substrate, such as a rectangular substrate for a flat panel display, or the like, among other shapes.
[0084] The plasma processing region **1302** within the CCP processing chamber **1301** is connected to a process gas supply system **1304**, such that one or more process gas(es) can be supplied in a controlled manner to the plasma processing region **1302**, as represented by line **1306**. It should be understood that the process gas supply system **1304** includes one or more process gas sources and an arrangement of valves and mass flow controllers to enable provision of the one or more process

gas(es) to the plasma processing region **1302** with a controlled flow rate and with a controlled flow time. Also, in various embodiments, the one or more process gas(es) are delivered to the plasma processing region **1302** in both a temporally controlled manner and a spatially controlled manner relative to the substrate **1305**. In various embodiments, the CCP processing system **150**A operates by having the process gas supply system **1304** deliver one or more process gases into the plasma processing region **1302**, and by applying RF power to the one or more process gases to transform the one or more process gases into the plasma **1323** in exposure to the substrate **1305**, in order to cause a change in material or surface condition on the substrate **1305**.

[0085] The CCP processing chamber **1301** includes a substrate support structure **1303** upon which the substrate **1305** is positioned and supported during processing operations. In some embodiments, an electrode **1307** is disposed within the substrate support structure **1303** to provide for transmission of RF power from the electrode **1307** through the plasma processing region **1302** to generate the plasma **1323** and/or control ion energy. The electrode **1307** is connected to receive RF power through the RF feed structure **160**, which is connected to the RF signal supply system **1100** by way of the impedance matching system **1115**. The RF feed structure **160** is an electrically conductive member. In some embodiments, the RF feed structure **160** includes an electrically conductive rod. The impedance matching system **1115** includes an arrangement of capacitors and inductors configured to ensure that the impedances seen at the outputs of the RF signal generators **101**, **102**, and **1101-1** through **1101-**N within the RF signal supply system **1100** are sufficiently close to design basis impedances for which the RF signal generators are designed to operate (usually 50 Ohm), so that RF power generated and transmitted by the RF signal generators **101**, **102**, and **1101-1** through **1101-**N will be transmitted into the plasma processing region **1302** as efficiently as possible, e.g., with minimum possible reflection.

[0086] Also, in some embodiments, the CCP processing chamber **1301** can include an upper electrode **1315**. In various embodiments, the upper electrode **1315** can provide either an electrical ground electrode or can be used to transmit RF power into the plasma processing region **1302**. For example, in some embodiments, the upper electrode **1315** is connected to a reference ground potential **1308**, such that the upper electrode **1315** provides a return path for RF signals transmitted into the plasma processing region **1302** from the electrode **1307**. Alternatively, in some embodiments, the upper electrode **1315** is connected to receive RF power through an RF feed structure **1317**, which is connected to an instance of the RF signal supply system **1100** by way of an instance of the impedance matching system **1115**.

[0087] In some embodiments, a heater assembly **1325** is disposed within the substrate support structure **1303** to provide temperature control of the substrate **1305**. The heater assembly **1325** is electrically connected to receive electrical power through an electrical connection **1327**, where the electrical power is supplied from a power supply **1331** through an electrical connection **1337** to an RF filter **1329**, and through the RF filter **1329** to the electrical connection **1327**. In some embodiments, the power supply **1331** is an alternating current (AC) power supply. In some embodiments, the power supply **1331** is a direct current (DC) power supply. In some embodiments, the heater assembly **1325** includes a plurality of electrical resistance heating elements. The RF filter **1329** is configured to prevent RF power from entering the power supply **1331**, while allowing transmission of electrical current between the power supply **1331** and the electrical connection **1327**.

[0088] Also, in some embodiments, a bias voltage control system **1365** is connected to the substrate support structure **1303** within the CCP processing chamber **1301**. In some embodiments, the bias voltage control system **1365** is connected to one or more bias voltage electrodes disposed within the substrate support structure **1303** to control a bias voltage present at the location of the substrate **1305**. The bias voltage can be controlled to attract charged constituents of the plasma **1323** toward the substrate **1305** and thereby control energy and directionality of the charged constituents of the plasma **1323**. For example, the bias voltage control system **1365** can be operated to accelerate ions in the plasma **1323** toward the substrate **1305** to perform an anisotropic etch on the substrate **1305**.

[0089] FIG. **13**B shows an example vertical cross-section diagram of an ICP processing system **150**B, in accordance with some embodiments of the present disclosure. The ICP processing system **150**B can also be referred to as a transformer coupled plasma (TCP) processing system. For ease of discussion herein, ICP processing system will be used to refer to both ICP and TCP processing systems. The ICP processing system **150**B includes a chamber **1351** within which a plasma processing region **1352** exists. Within the plasma processing region **1352**, the plasma **1323** (represented by the dashed oval region) is generated in exposure to the substrate **1305** to affect a change to the substrate **1305** in a controlled manner. In various fabrication processes, the change to the substrate **1305** can be a change in material or surface condition on the substrate **1305**. For example, in various fabrication processes, the change to the substrate **1305** can include one or more of etching of a material from the substrate **1305**, deposition of a material on the substrate **1305**, or modification of material present on the substrate **1305**. It should be understood that the ICP processing chamber **1351** can be any type of ICP processing chamber in which RF power is transmitted from a coil **1355** disposed outside the ICP processing chamber **1351** to a process gas within the ICP processing chamber **1351** to generate the plasma **1323** within the plasma processing region **1352**. An upper window structure **1353** is provided to allow for transmission of RF power from the coil **1355** through the upper window structure **1353** and into the plasma processing region **1352** of the ICP processing chamber **1351**.

[0090] The plasma processing region **1352** within the ICP processing chamber **1351** is connected to the process gas supply system **1304**, such that one or more process gas(es) can be supplied in a controlled manner to the plasma processing region **1352**, as represented by line **1306**. The ICP processing system **150**B operates by having the process gas supply system **1304** flow one or more process gases into the plasma processing region **1352**, and by applying RF power from the coil **1355** to the one or more process gases to transform the one or more process gases into the plasma **1323** in exposure to the substrate **1305**, in order to cause a change in material or surface condition on the substrate **1305**.

[0091] The coil **1355** is disposed above the upper window structure **1353**. In the example of FIG. **13**B, the coil **1355** is formed as a radial coil assembly, with the shaded parts of the coil **1355** turning into the page of the drawing and with the unshaded parts of the coil **1355** turning out of the page of the drawing. FIG. **13**C shows a top view of the coil **1355**, in accordance with some embodiments. It should be understood, however, that in other embodiments the coil **1355** can have essentially any configuration that is suitable for transmitting RF power through the upper window structure **1353** and into the plasma processing region **1352**. In various embodiments, the coil **1355** can have any number of turns and any cross-section size and shape (circular, oval, rectangular, trapezoidal, etc.) as appropriate to provide the desired transmission of RF power through the upper window structure **1353** into the plasma processing region **1352**. In some embodiments, the coil **1355** is connected through an RF power supply structure **1361** to an instance of the RF signal supply system **1100** by way of impedance matching system **1115**. Also, in some embodiments, the ICP processing chamber **1351** can include the electrode **1307**, the RF feed structure **160**, the impedance matching system **1115**, and the RF signal supply system **110**, as previously described with regard to FIG. **13**A.

[0092] Also, in some embodiments, the ICP processing chamber **1351** can include the heater assembly **1325** disposed within the substrate support structure **1303** to provide temperature control of the substrate **1305**. As described with regard to the CCP processing chamber **1301** of FIG. **13**A, the heater assembly **1325** of the ICP processing chamber **1351** is electrically connected to receive electrical power through the electrical connection **1327**, where the electrical power is supplied from the power supply **1331** through the electrical connection **1337** to the RF filter **1329**, and through the RF filter **1329** to the electrical connection **1327**. Also, in some embodiments, the bias voltage control system **1365** is connected to the substrate support structure **1303** within the ICP processing chamber **1351**.

[0093] The control module **163** is configured and connected to provide for control of plasma process operations performed by the CCP processing system **150**A and by the ICP processing system **150**B. In some embodiments, the control module **163** is implemented as a combination of computer hardware and software. The control module **163** can be configured and connected to provide for control of essentially any system or component associated with the CCP processing system **150**A and/or the ICP processing system **150**B. For example, the control module **163** can be configured and connected to control the process gas supply system **1304**, the RF signal supply system **1100**, the impedance matching system **1115**, the power supply **1331** for the heater assembly **1325**, the bias voltage control system **1365**, and/or any other system or component.

[0094] A lso, the control module **163** can be connected and configured to receive signals from various components, sensors, and monitoring devices associated with the CCP processing system **150**A and the ICP processing system **150**B. For example, the control module **163** can be connected and configured to receive electrical measurement signals, e.g., voltage and/or current, and RF measurement signals from one or more of the substrate support structure **1303**, the RF feed structure **160**, the RF feed structure **1317**, the RF feed structure **1361**, the electrical connection **1327**, and from any other structure or component within the CCP processing system **150**A and the ICP processing system **150**B. And, the control module **163** can be connected and configured to receive temperature and pressure measurement signals from within the plasma processing regions **1302** and **1352** of the CCP processing chamber **1301** and the ICP processing chamber **1351**, respectively. Also, in some embodiments, the control module **163** can be configured and connected to receive, process, and respond to an optically measured signal within the CCP processing chamber **1301** and the ICP processing chamber **1351**.

[0095] It should be understood that the control module **163** can be connected and configured to control essentially any active device, i.e., controllable device, associated with operation of the CCP processing system **150**A and the ICP processing system **150**B. And, it should be understood that the control module **163** can be connected and configured to monitor essentially any physical and/or electrical state, condition, and/or parameter at essentially any location within the CCP processing system **150**A and the ICP processing system **150**B. The control module **163** can also be configured to direct operation of various components in a synchronous and scheduled manner to perform a prescribed plasma processing operation on the substrate **1305**. For example, the control module **163** can be configured to operate the CCP processing system **150**A and the ICP processing system **150**B by executing process input and control instructions/programs. The process input and control instructions/programs may include process recipes having time-dependent directions for parameters such as power levels, timing parameters, process gases, mechanical movement of the substrate **1305**, etc., as needed to obtain a desired process result on the substrate **1305**. In some embodiments, the control module **163** is programmed to direct operation of the CCP processing system **150**A and/or the ICP processing system **150**B in accordance with the frequency tuning process of FIG. **2**.

[0096] FIG. **13**D shows a diagram of the control module **163**, in accordance with some example embodiments. The control module **163** includes a processor **1381**, a storage hardware unit (HU) **1383** (e.g., memory), an input HU **1371**, an output HU **1375**, an input/output (I/O) interface **1373**, an I/O interface **1377**, the NIC **152**, and a data communication bus **1385**. The processor **1381**, the storage HU **1383**, the input HU **1371**, the output HU **1375**, the I/O interface **1373**, the I/O interface **1377**, and the NIC **152** are in data communication with each other by way of the data communication bus **1385**. Examples of the input HU **1371** include a mouse, a keyboard, a stylus, a data acquisition system, a data acquisition card, etc. Examples of the output HU **1375** include a display, a speaker, a device controller, etc. Examples of the NIC **152** include a network interface card, a network adapter, etc. In various embodiments, the NIC **152** is configured to operate in accordance with one or more communication protocols and associate physical layers, such as

Ethernet and/or EtherCAT, among others. Each of the I/O interfaces **1373** and **1377** is defined to provide compatibility between different hardware units coupled to the I/O interface. For example, the I/O interface **1373** can be defined to convert a signal received from the input HU **1371** into a form, amplitude, and/or speed compatible with the data communication bus **1385**. Also, the I/O interface **1377** can be defined to convert a signal received from the data communication bus **1385** into a form, amplitude, and/or speed compatible with the output HU **1375**. Although various operations described herein are performed by the processor **1381** of the control module **163**, it should be understood that in some embodiments various operations can be performed by multiple processors of the control module **163** and/or by multiple processors of multiple computing systems connected to the control module **163**.

[0097] An RF signal supply system (**1100**) for a plasma processing system (**150**) is disclosed herein. The RF signal supply system (**1100**) includes a first RF signal generator (**101**) set to generate a first RF signal having a first frequency (LF.sub.1) at an output (**110**) of the first RF signal generator (**101**). The RF signal supply system (**1100**) also includes a second RF signal generator (**1101-1**) set to generate a second RF signal having a second frequency (LF.sub.2) at an output (**1110-1**) of the second RF signal generator (**1101-1**). The second frequency (LF.sub.2) is a specified harmonic of the first frequency (LF.sub.1), i.e., LF.sub.2≈(LF.sub.1*n), where n is an integer greater than 1. The RF signal supply system (**1100**) also includes a third RF signal generator (**1101-2**) set to generate a third RF signal having a third frequency (LF.sub.3) at an output (**1110-2**) of the third RF signal generator (**1101-2**). The third frequency (LF.sub.3) is a specified harmonic of the first frequency (LF.sub.1), i.e., LF.sub.3≈(LF.sub.1*n), where n is an integer greater than 1. And, the third frequency (LF.sub.3) and the second frequency (LF.sub.2) are different specified harmonics of the first frequency (LF.sub.1). The RF signal supply system (**1100**) also includes a fourth RF signal generator (**102**) set to generate a fourth RF signal having a fourth frequency (HF) at an output (**171**) of the fourth RF signal generator (**102**). The fourth frequency (HF) is at least two orders of magnitude larger than the first frequency (LF.sub.1).

[0098] The RF signal supply system (**1100**) also includes an impedance matching system (**1115**) having a first input (**117**) connected to the output (**110**) of the first RF signal generator (**101**), and a second input (**1117-1**) connected to the output (**1110-1**) of the second RF signal generator (**1101-1**), and a third input (**1117-2**) connected to the output (**1110-2**) of the third RF signal generator (**1101-2**), and a fourth input (**175**) connected to the output (**171**) of the fourth RF signal generator (**102**). The impedance matching system (**1115**) has an output (**123**) connected to an RF supply input (**160**) of the plasma processing system (**150**). The impedance matching system (**1115**) is configured to control impedances at the output (**110**) of the first RF signal generator (**101**), and at the output (**1110-1**) of the second RF signal generator (**1101-1**), and at the output (**1110-2**) of the third RF signal generator (**1101-2**), and at the output (**171**) of the fourth RF signal generator (**102**).

[0099] The RF signal supply system (**1100**) also includes a control module (**163**) programmed to control a first phase difference (Δϕ.sub.1) between the second RF signal having the second frequency (LF.sub.2) and the first RF signal having the first frequency (LF.sub.1). The control module (**163**) is also programmed to control a second phase difference (Δϕ.sub.2) between the third RF signal having the third frequency (LF.sub.3) and the first RF signal having the first frequency (LF.sub.1). The control module (**163**) is also programmed to control a first voltage difference (ΔV.sub.1) between the second RF signal having the second frequency (LF.sub.2) and the first RF signal having the first frequency (LF.sub.1). The control module (**163**) is also programmed to control a second voltage difference (ΔV.sub.2) between the third RF signal having the third frequency (LF.sub.3) and the first RF signal having the first frequency (LF.sub.1). The first phase difference (Δϕ.sub.1), and the second phase difference (Δϕ.sub.2), and the first voltage difference (ΔV.sub.1), and the second voltage difference (ΔV.sub.2) are set to collectively control a plasma sheath voltage/potential as a function of time within the plasma processing system (**150**) and correspondingly control a process result uniformity across a substrate (**1305**) within the plasma processing system (**150**).

[0100] In some embodiments, the first frequency (LF.sub.1) is within a range extending from about 330 kHz to about 440 kHz, and the fourth frequency (HF) is within a range extending from about 57 MHz to about 63 MHz. In some embodiments, the first frequency (LF.sub.1) is about 400 kHz, and the second frequency (LF.sub.2) is about 1.2 MHz, and the third frequency (LF.sub.3) is about 2.0 MHz, and the fourth frequency (HF) is about 60 MHz. In some embodiments, the first phase difference (Δϕ.sub.1) is about thirty degrees, and the second phase difference (Δϕ.sub.2) is about thirty degrees. In some embodiments, the first voltage difference (ΔV.sub.1) is set so that a power of the second RF signal having the second frequency (LF.sub.2) is within a range extending from about 17% to about 20% of a power of the first RF signal having the frequency (LF.sub.1), and the second voltage difference (ΔV.sub.2) is set so that a power of the third RF signal having the frequency (LF.sub.3) is within a range extending from about 5% to about 8% of a power of the first RF signal having the frequency (LF.sub.1). In some embodiments, each of the second frequency (LF.sub.2) and third frequency (LF.sub.3) is a respective integer multiple greater than one of the first frequency (LF.sub.1).

[0101] In some embodiments, the second RF signal generator (**1101-1**) is connected as a slave of the first RF signal generator (**101**) so that the second frequency (LF.sub.2) tracks in real-time as an integer multiple of the first frequency (LF.sub.1), and so that the first phase difference (Δϕ.sub.1) between the second RF signal having the second frequency (LF.sub.2) and the first RF signal having the first frequency (LF.sub.1) is maintained in real-time. Also, in these embodiments, the third RF signal generator (**1101-2**) is connected as a slave of the first RF signal generator (**101**) so that the third frequency (LF.sub.3) tracks in real-time as an integer multiple of the first frequency (LF.sub.1), and so that the second phase difference (Δϕ.sub.2) between the third RF signal having the third frequency (LF.sub.3) and the first RF signal having the first frequency (LF.sub.1) is maintained in real-time.

[0102] In some embodiments, the first phase difference (Δϕ.sub.1), and the first voltage difference (ΔV.sub.1), and the second phase difference (Δϕ.sub.2), and the second voltage difference (ΔV.sub.2) are collectively set to control an etch rate uniformity across a substrate (**1305**) within the plasma processing system (**150**). In some embodiments, the first phase difference (Δϕ.sub.1), and the first voltage difference (ΔV.sub.1), and the second phase difference (Δϕ.sub.2), and the second voltage difference (ΔV.sub.2) are collectively set to increase a plasma sheath voltage/potential over a larger percentage of a cycle of the first RF signal having the first frequency (LF.sub.1). In some embodiments, the first phase difference (Δϕ.sub.1), and the first voltage difference (ΔV.sub.1), and the second phase difference (Δϕ.sub.2), and the second voltage difference (ΔV.sub.2) are collectively set to generate a substantially square cyclical waveform as a combination of the first RF signal having the first frequency (LF.sub.1), and the second RF signal having the second frequency (LF.sub.2) and the third RF signal having the third frequency (LF.sub.3). In some embodiments, the first phase difference (Δϕ.sub.1), and the first voltage difference (ΔV.sub.1), and the second phase difference (Δϕ.sub.2), and the second voltage difference (ΔV.sub.2) are collectively set to provide a larger maximum plasma sheath voltage/potential than what is achievable from just the first RF signal having the first frequency (LF.sub.1). In some embodiments, the first RF signal having the first frequency (LF.sub.1), and the second RF signal having the second frequency (LF.sub.2), and the third RF signal having the third frequency (LF.sub.3) combine to form a cyclical waveform, where each cycle of the cyclical waveform has a negative half and a positive half, and where the first phase difference (Δϕ.sub.1), and the first voltage difference (ΔV.sub.1), and the second phase difference (Δϕ.sub.2), and the second voltage difference (ΔV.sub.2) are collectively set so that the negative half of each cycle of the cyclical waveform is longer than the positive half of each cycle of the cyclical waveform.

[0103] In some embodiments, the impedance matching system (**1115**) includes a first impedance control circuit (**1202**) connected between the first input (**117**) of the impedance matching system

(**1115**) and the output (**123**) of the impedance matching system (**1115**). And, the impedance matching system (**1115**) includes a second impedance control circuit (**1206-1**) connected between the second input (**1117-1**) of the impedance matching system (**1115**) and the output (**123**) of the impedance matching system (**1115**). And, the impedance matching system (**1115**) includes a third impedance control circuit (**1206-2**) connected between the third input (**1117-2**) of the impedance matching system (**1115**) and the output (**123**) of the impedance matching system (**1115**). And, the impedance matching system (**1115**) includes a fourth impedance control circuit (**1208**) connected between the fourth input (**175**) of the impedance matching system (**1115**) and the output (**123**) of the impedance matching system (**1115**).

[0104] FIG. **14** shows a flowchart of a method for operating a radiofrequency signal generator system for a plasma processing system, in accordance with some embodiments. It should be understood that the operations of FIG. **14** can be performed in a substantially simultaneous manner, although for description purposes some of the operations appear as though done in sequence within the flowchart of FIG. **14**. The method includes an operation **1401** for operating a first RF signal generator (**101**) to generate a first RF signal having a first frequency (LF.sub.1) at an output (**110**) of the first RF signal generator (**101**). The method also includes an operation **1403** for operating a second RF signal generator (**1101-1**) to generate a second RF signal having a second frequency (LF.sub.2) at an output (**1110-1**) of the second RF signal generator (**1101-2**). The second frequency (LF.sub.2) is a specified harmonic of the first frequency (LF.sub.1), i.e., LF.sub.2≈(LF.sub.1*n), where n is an integer greater than 1. The method also includes an operation **1405** for operating a third RF signal generator (**1101-2**) to generate a third RF signal having a third frequency (LF.sub.3) at an output (**1110-2**) of the third RF signal generator (**1101-2**). The third frequency (LF.sub.3) is a specified harmonic of the first frequency (LF.sub.1), i.e., LF.sub.3 ˜ (LF.sub.1*n), where n is an integer greater than 1. The third frequency (LF.sub.3) and the second frequency (LF.sub.2) are different specified harmonics of the first frequency (LF.sub.1). The method also includes an operation **1407** for operating a fourth RF signal generator (**102**) to generate a fourth RF signal having a fourth frequency (HF) at an output (**171**) of the fourth RF signal generator (**102**). The fourth frequency (HF) is at least two orders of magnitude larger than the first frequency (LF.sub.1).

[0105] The method also includes an operation **1409** for operating an impedance matching system (**1115**) to control impedances at the output (**110**) of the first RF signal generator (**101**), and at the output (**1110-1**) of the second RF signal generator (**1101-1**), and at the output (**1110-2**) of the third RF signal generator (**1101-2**), and at the output (**171**) of the fourth RF signal generator (**102**). The first RF signal having the first frequency (LF.sub.1), the second RF signal having the second frequency (LF.sub.2), the third RF signal having the third frequency (LF.sub.3), and the fourth RF signal having the fourth frequency (HF) are transmitted through the impedance matching system (**1115**) to a radiofrequency supply input (**160**) of the plasma processing system (**150**) causing generation of a plasma (**1323**) within the plasma processing system (**150**). The impedance matching system (**1115**) is operated to combine the first RF signal having the first frequency (LF.sub.1), the second RF signal having the second frequency (LF.sub.2), the third RF signal having the third frequency (LF.sub.3), and the fourth RF signal having the fourth frequency (LF.sub.4) onto the output of the impedance matching system (**1115**).

[0106] The method also includes an operation **1411** for operating a control module (**163**) to control a first phase difference (Δϕ.sub.1) between the second RF signal having the second frequency (LF.sub.2) and the first RF signal having the first frequency (LF.sub.1). The operation **1411** also includes operating the control module (**163**) to control a second phase difference (Δϕ.sub.2) between the third RF signal having the third frequency (LF.sub.3) and the first RF signal having the first frequency (LF.sub.1). The operation **1411** also includes operating the control module (**163**) to control a first voltage difference (ΔV.sub.1) between the second RF signal having the second frequency (LF.sub.2) and the first RF signal having the first frequency (LF.sub.1). The operation **1411** also includes operating the control module (**163**) to control a second voltage difference

(ΔV.sub.2) between the third RF signal having the third frequency (LF.sub.3) and the first RF signal having the first frequency (LF.sub.1). The first phase difference (Δϕ.sub.1), the second phase difference (Δϕ.sub.2), the first voltage difference (ΔV.sub.1), and the second voltage difference (ΔV.sub.2) collectively control a plasma sheath voltage/potential as a function of time within the plasma processing system (**150**). In some embodiments, the plasma sheath voltage/potential is used to control a process result uniformity across a substrate (**1305**) within the plasma processing system (**150**).

[0107] In some embodiments of the method, the first frequency (LF.sub.1) is within a range extending from about 340 kHz to about 440 kHz, and the fourth frequency (HF) is within a range extending from about 57 MHz to about 63 MHz, with each of the second frequency (LF.sub.2) and third frequency (LF.sub.3) being a respective integer multiple greater than one of the first frequency (LF.sub.1). In some embodiments of the method, the first frequency (LF.sub.1) is about 400 kHz, and the second frequency (LF.sub.2) is about 1.2 MHz, and the third frequency (LF.sub.3) is about 2.0 MHz, and the fourth frequency (HF) is about 60 MHz. In some embodiments of the method, the first phase difference (Δϕ.sub.1) is about thirty degrees, and the second phase difference (Δϕ.sub.2) is about thirty degrees. In some embodiments of the method, the first voltage difference (ΔV.sub.1) is controlled so that a power of the second RF signal having the second frequency (LF.sub.2) is within a range extending from about 17% to about 20% of a power of the first RF signal having the frequency (LF.sub.1), and the second voltage difference (ΔV.sub.2) is controlled so that a power of the third RF signal having the frequency (LF.sub.3) is within a range extending from about 5% to about 8% of a power of the first RF signal having the frequency (LF.sub.1).

[0108] In some embodiments of the method, the second RF signal generator (**1101-1**) is operated as a slave of the first RF signal generator (**101**) to cause the second frequency (LF.sub.2) to track in real-time as an integer multiple of the first frequency (LF.sub.1), and to cause the first phase difference (Δϕ.sub.1) between the second RF signal having the second frequency (LF.sub.2) and the first RF signal having the first frequency (LF.sub.1) to be maintained in real-time. Also, in these embodiments of the method, the third RF signal generator (**1101-2**) is operated as a slave of the first RF signal generator (**101**) to cause the third frequency (LF.sub.3) to track in real-time as an integer multiple of the first frequency (LF.sub.1), and to cause the second phase difference (Δϕ.sub.2) between the third RF signal having the third frequency (LF.sub.3) and the first RF signal having the first frequency (LF.sub.1) to be maintained in real-time.

[0109] In some embodiments, the first phase difference (Δϕ.sub.1), and the second phase difference (Δϕ.sub.2), and the first voltage difference (ΔV.sub.1), and the second voltage difference (ΔV.sub.2) are collectively set to control an etch rate uniformity across a substrate (**1305**) within the plasma processing system (**150**). In some embodiments, the first phase difference (Δϕ.sub.1), and the second phase difference (Δϕ.sub.2), and the first voltage difference (ΔV.sub.1), and the second voltage difference (ΔV.sub.2) are collectively set to increase a plasma sheath voltage/potential over a larger percentage of a cycle of the first RF signal having the first frequency (LF.sub.1). In some embodiments, the first phase difference (Δϕ.sub.1), and the first voltage difference (ΔV.sub.1), and the second phase difference (Δϕ.sub.2), and the second voltage difference (ΔV.sub.2) are collectively controlled so that a combination of the first RF signal having the first frequency (LF.sub.1), and the second RF signal having the second frequency (LF.sub.2), and the third RF signal having the third frequency (LF.sub.3) generates a substantially square cyclical waveform. In some embodiments, the first phase difference (**401**), and the first voltage difference (ΔV.sub.1), and the second phase difference (Δϕ.sub.2), and the second voltage difference (ΔV.sub.2) are collectively controlled to provide a larger maximum plasma sheath voltage/potential than what is achievable from just the first RF signal having the first frequency (LF.sub.1). In some embodiments, the first RF signal having the first frequency (LF.sub.1), and the second RF signal having the second frequency (LF.sub.2), and the third RF signal having the third frequency (LF.sub.3) combine to form a cyclical waveform, where each cycle of the cyclical waveform has a negative half and a positive half, and where the first phase difference (Δϕ.sub.1), and the first voltage difference (ΔV.sub.1), and the second phase difference (Δϕ.sub.2), and the second voltage difference (ΔV.sub.2) are collectively controlled so that the negative half of each cycle of the cyclical waveform is longer than the positive half of each cycle of the cyclical waveform.

[0110] In the embodiments described above, multiple harmonic frequency signals are combined with a fundamental (base) frequency signal to create a composite low frequency RF signal waveform for use in the frequency tuning process of FIG. **2** in which a high frequency RF signal is applied in conjunction with the composite low frequency RF signal waveform to generate plasma for processing a semiconductor substrate. In some embodiments, either lieu of or in addition to, a passive approach can be implemented to manipulate one or more harmonic frequency signals of the fundamental (base) low frequency RF signal to create an engineered low frequency RF signal waveform for use in the frequency tuning process of FIG. **2**. For example, in some embodiments of the passive approach, one or more RF signal filters can be disposed with various RF signal transmission paths within and/or around the plasma processing chamber **150** in order to manipulate one or more harmonic frequency signals of the fundamental (base) low frequency RF signal to create the engineered low frequency RF signal waveform for use in the frequency tuning process of FIG. **2**. Also, in some embodiments, impedances of various chamber parts within the various RF signal transmission paths within and/or around the plasma processing chamber **150** can be engineered to contribute to manipulation of one or more harmonic frequency signals of the fundamental (base) low frequency RF signal to create the engineered low frequency RF signal waveform for use in the frequency tuning process of FIG. **2**.

[0111] In some embodiments, the RF signal filters are configured to filter and/or change a phase of particular harmonic frequency signal relative to a phase of the fundamental (base) low frequency RF signal. In various embodiments, the RF signal filter can be implemented in either the low frequency RF signal generator **101** or the impedance matching system **115**/**1115**. In the passive approach, the objective is to control a phase difference between one or more harmonic frequency signals and the corresponding fundamental (base) frequency signal in order to achieve a desired shape of the engineered low frequency RF signal waveform, and in turn achieve a desired plasma sheath voltage/potential behavior as a function of time that will have a beneficial effect on plasma process result uniformity control across the substrate. In the passive approach, impedance control is implemented within the RF transmission path(s) to affect phase control of the targeted low frequency harmonic signals and in turn achieve a desired shape of the engineered low frequency RF signal waveform. In some embodiments, the phase of particular low frequency harmonic signals can also be filtered/changed either electrically or by tuning some impedance along the RF signal transmission path, such as within the plasma processing chamber **1301**/**1351**.

[0112] For example, an impedance control device, such as a variable capacitor or other device, is connected between an electrode and a reference ground potential in order to change the impedance to ground as seen by the particular harmonic frequency signals of the low frequency RF signal, which in turn changes the phase of the particular harmonic frequency signals and correspondingly changes the shape of the engineered low frequency RF signal waveform used in the frequency tuning process of FIG. **2**. For example, with reference to FIG. **13**A, in some embodiments a variable capacitor or other impedance control device is connected between the electrode **1315** and the reference ground potential **1308** in order to change the phase of one or more particular harmonic frequency signals and correspondingly change the shape of the engineered low frequency RF signal waveform used in the frequency tuning process of FIG. **2**. It should be understood that in various embodiments, one or more impedance control devices can be installed at specified location(s) within the RF signal transmission path to achieve a desired effect on the phase(s) of one or more particular harmonic frequency signal(s) of the fundamental (base) low frequency RF signal as generated by the low frequency RF signal generator **101**, in order to achieve a desired shape of the engineered low frequency RF signal waveform, and in turn achieve a desired plasma sheath voltage/potential behavior as a function of time that will have a beneficial effect on plasma process result uniformity control across the substrate.

[0113] It should be understood that the embodiments described herein can employ various computer-implemented operations involving data stored in computer systems. These operations are those requiring physical manipulation of physical quantities. Any of the operations described herein that form part of the embodiments are useful machine operations. The embodiments also relate to a hardware unit or an apparatus for performing these operations. The apparatus may be specially constructed for a special purpose computer. When defined as a special purpose computer, the computer can also perform other processing, program execution or routines that are not part of the special purpose, while still being capable of operating for the special purpose. In some embodiments, the operations may be processed by a general purpose computer selectively activated or configured by one or more computer programs stored in the computer memory, cache, or obtained over a network. When data is obtained over a network, the data may be processed by other computers on the network, e.g., a cloud of computing resources.

[0114] Various embodiments described herein can be fabricated as computer-readable code on a non-transitory computer-readable medium. The non-transitory computer-readable medium is any data storage hardware unit that can store data, which can be thereafter be read by a computer system. Examples of the non-transitory computer-readable medium include hard drives, network attached storage (NAS), ROM, RAM, compact disc-ROM s (CD-ROMs), CD-recordables (CD-Rs), CD-rewritables (CD-RWs), magnetic tapes, and other optical and non-optical data storage hardware units. The non-transitory computer-readable medium can include computer-readable tangible medium distributed over a network-coupled computer system so that the computer-readable code is stored and executed in a distributed fashion.

[0115] Although the foregoing disclosure includes some detail for purposes of clarity of understanding, it will be apparent that certain changes and modifications can be practiced within the scope of the appended claims. For example, it should be understood that one or more features from any embodiment disclosed herein may be combined with one or more features of any other embodiment disclosed herein. Accordingly, the present embodiments are to be considered as illustrative and not restrictive, and what is claimed is not to be limited to the details given herein, but may be modified within the scope and equivalents of the described embodiments.

Claims

1. A radiofrequency (RF) signal supply system for a plasma processing system, comprising: a first RF signal generator set to generate a first RF signal having a first frequency; a second RF signal generator set to generate a second RF signal having a second frequency, the second frequency being a specified harmonic of the first frequency; and a third RF signal generator set to generate a third RF signal having a third frequency, the third frequency being at least two orders of magnitude larger than the first frequency, wherein the first RF signal, the second RF signal, and the third RF signal are supplied to the plasma processing system.

2. The RF signal supply system for the plasma processing system as recited in claim 1, wherein the first frequency is within a range extending from about 330 kiloHertz (kHz) to about 440 kHz, and the third frequency is within a range extending from about 54 megaHertz (MHz) to about 63 MHz.

3. The RF signal supply system for the plasma processing system as recited in claim 1, wherein the first frequency is about 400 kiloHertz (KHz), and the second frequency is about 1.2 megaHertz (MHz), and the third frequency is about 60 MHz.

4. The RF signal supply system for the plasma processing system as recited in claim 1, wherein the second RF signal generator is connected as a slave of the first RF signal generator so that the

second frequency tracks in real-time as an integer multiple of the first frequency.
5. The RF signal supply system for the plasma processing system as recited in claim 1, further comprising: an impedance matching system connected between the plasma processing system and each of the first RF signal generator, the second RF signal generator, and the third RF signal generator, the impedance matching system configured to combine the first RF signal, the second RF signal, and the third RF signal onto an output of the impedance matching system connected to the plasma processing system.
6. The RF signal supply system for the plasma processing system as recited in claim 5, wherein the impedance matching system includes a first impedance control circuit connected to an output of the first RF signal generator, a second impedance control circuit connected to an output of the second RF signal generator, and a third impedance control circuit connected to an output of the third RF signal generator.
7. The RF signal supply system for the plasma processing system as recited in claim 6, wherein each of the first impedance control circuit, the second impedance control circuit, and the third impedance control circuit respectively include at least one capacitor and at least one inductor.
8. The RF signal supply system for the plasma processing system as recited in claim 7, wherein the first impedance control circuit has an output node connected to a pre-output node of the impedance matching system, and the second impedance control circuit has an output node connected to the pre-output node of the impedance matching system, wherein the pre-output node of the impedance matching system is electrically connected through an output inductor to the output of the impedance matching system, and wherein the third impedance control circuit has an output node connected directly to the output of the impedance matching system.
9. The RF signal supply system for the plasma processing system as recited in claim 8, wherein the first impedance control circuit includes two serially connected inductors electrically connected in series with a capacitor.
10. The RF signal supply system for the plasma processing system as recited in claim 9, wherein each terminal of each of the two serially connected inductors is electrically connected to another respective capacitor that has an output terminal electrically connected to a reference ground potential.
11. The RF signal supply system for the plasma processing system as recited in claim 10, wherein the second impedance control circuit is electrically configured in a same manner as the first impedance control circuit.
12. The RF signal supply system for the plasma processing system as recited in claim 11, wherein the third impedance control circuit includes an inductor electrically connected in series with a capacitor.
13. The RF signal supply system for the plasma processing system as recited in claim 12, wherein an input terminal of the capacitor of the third impedance control circuit is electrically connected to another capacitor of the third impedance control circuit that has an output terminal electrically connected to the reference ground potential, and the input terminal of the capacitor of the third impedance control circuit is electrically connected to another inductor of the third impedance control circuit that has an output terminal electrically connected to the reference ground potential.
14. The RF signal supply system for the plasma processing system as recited in claim 5, further comprising: a control module configured to control a phase difference between the first RF signal and the second RF signal, the control module configured to control a voltage difference between the first RF signal and the second RF signal.
15. The RF signal supply system for the plasma processing system as recited in claim 14, wherein the control module is configured to control the phase difference between the first RF signal and the second RF signal and the voltage difference between the first RF signal and the second RF signal so as to control a plasma sheath voltage as a function of time within the plasma processing system.
16. The RF signal supply system for the plasma processing system as recited in claim 14, wherein

the control module is configured to control the phase difference between the first RF signal and the second RF signal to be about thirty degrees, and wherein the control module is configured to control the voltage difference between the first RF signal and the second RF signal so that a power of the second RF signal is within a range extending from about 17% to about 20% of a power of the first RF signal.

17. The RF signal supply system for the plasma processing system as recited in claim 14, wherein the control module is configured to control the phase difference between the first RF signal and the second RF signal and the voltage difference between the first RF signal and the second RF signal so as to control an etch rate uniformity across a substrate within the plasma processing system.

18. The RF signal supply system for the plasma processing system as recited in claim 14, wherein the control module is configured to control the phase difference between the first RF signal and the second RF signal and the voltage difference between the first RF signal and the second RF signal so as to increase a plasma sheath voltage within the plasma processing system over a larger percentage of a cycle of the first RF signal.

19. The RF signal supply system for the plasma processing system as recited in claim 14, wherein the control module is configured to control the phase difference between the first RF signal and the second RF signal and the voltage difference between the first RF signal and the second RF signal so as to generate a substantially square cyclical waveform as a combination of the first RF signal and the second RF signal.

20. The RF signal supply system for the plasma processing system as recited in claim 14, wherein the control module is configured to control the phase difference between the first RF signal and the second RF signal and the voltage difference between the first RF signal and the second RF signal so as to provide a larger maximum plasma sheath voltage within the plasma processing chamber than what is achievable from just the first RF signal.