

Summary

[0006] Embodiments of the disclosure provide apparatus, methods and computer programs for chamber matching using a voltage control mode. It should be appreciated that the present embodiments can be implemented in numerous ways, e.g., a process, an apparatus, a system, a device, or a method on a computer-readable medium. Several embodiments are described below.

[0007] In some embodiments, a voltage control mode is used to perform chamber-to-chamber matching and/or to perform intra-chamber matching. The voltage control mode is used to reduce variability in characteristics of one or more plasma chambers. The variability in characteristics of one or more plasma chambers creates harmonics that add a variation to a fundamental waveform. By measuring and extracting the harmonics, the variability in characteristics is accounted for. Based on the harmonics, power supplied to a plasma chamber is controlled and/or elements of a plasma system are replaced with other corresponding elements to reduce the effect of the harmonics on the one or more plasma chambers.

[0008] In several embodiments, a method for compensating for harmonics produced during plasma processing in a plasma chamber is described. The method includes retrieving a measurement of a combined waveform. The combined waveform includes a fundamental waveform and a harmonic waveform. The combined waveform defines a voltage proximate to a surface of a chuck, which is coupled to a radio frequency (RF) transmission line. The RF transmission line is coupled to an impedance matching circuit. The impedance matching circuit is coupled to an RF generator. The method further includes extracting the fundamental waveform from the combined waveform, determining a difference between a magnitude of the combined waveform and a magnitude of the fundamental waveform, and controlling the RF generator to compensate for the difference. The method is executed by one or more processors.

[0009] In a number of embodiments, a method for compensating for harmonics produced during plasma processing in a plasma chamber is described. The method includes retrieving a measurement of a combined waveform, which includes a fundamental waveform and a harmonic waveform. The combined waveform defines a ~~variable~~voltage proximate to a surface of a chuck, the chuck coupled to an RF transmission line, which is coupled to an impedance matching circuit. The impedance matching circuit is coupled to an RF generator.

DETAILED DESCRIPTION

[0023] The following embodiments describe systems and methods for chamber matching using a voltage control mode. It will be apparent that the present embodiments 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 embodiments.

[0024] Figure 1A shows an embodiment of a graph 102 used to illustrate chamber matching using a voltage control mode. The graph 102 plots voltage along a y-axis and time along an x-axis. A combined waveform W5, which is a sum of a fundamental waveform W0 and a fifth harmonic waveform of the fundamental waveform W0, is plotted and the combined waveform W5 has a phase of $\pi/3$ relative to a phase of the fundamental waveform W0.

[0025] The combined waveform W5 is generated when plasma is generated within a plasma chamber. For example, the combined waveform W5 plots a voltage of plasma within the plasma chamber.

[0026] The fundamental waveform W0 is extracted from the combined waveform W5.

[0027] A difference in a peak magnitude W5mag of the combined waveform W5 and a peak magnitude W0mag of the fundamental waveform W0 is determined. The peak magnitude W5mag of the combined waveform W5 is decreased to match the peak magnitude W0mag of the fundamental waveform W0.

[0028] In some embodiments, a peak magnitude of a waveform is a maximum magnitude of the waveform. For example, a sinusoidal waveform or a nearly sinusoidal waveform has peaks and valleys. A peak magnitude is a magnitude of peaks of the sinusoidal waveform or the nearly sinusoidal waveform. As another example, a peak magnitude is a maximum of all magnitudes of a waveform.

[0029] In several embodiments, instead of decreasing the peak magnitude W5mag to match the peak magnitude W0mag, when a peak magnitude of a combined waveform is less than the peak magnitude W0mag, the peak magnitude of the combined waveform is increased to match the peak magnitude W0mag.

[0030] In some embodiments, a difference ϕ_{W5W0} in phases of the combined waveform W5 and the fundamental waveform W0 is determined. For example, the difference ϕ_{W5W0} in phases of the combined waveform W5 and the fundamental waveform W0 when the combined waveform W5 achieves the peak magnitude $W5_{mag}$ and the fundamental waveform W0 achieves the peak magnitude $W0_{mag}$ is determined. The phase ϕ_{W5} of the combined waveform W5 is increased by the phase difference ϕ_{W5W0} between the phase ϕ_{W0} of the fundamental waveform W0 and the phase ϕ_{W5} of the combined waveform W5. In various embodiments, when the ϕ_{W5} of the combined waveform W5 is increased by the phase difference ϕ_{W5W0} , a peak magnitude of the combined waveform W5 aligns with a peak magnitude of the fundamental waveform W0.

[0031] In several embodiments, instead of increasing the phase ϕ_{W5} of the combined waveform W5 by the phase difference ϕ_{W5W0} , a phase of a combined waveform (not shown) is decreased by a phase difference between the fundamental waveform W0 and the combined waveform to align a peak magnitude of the fundamental waveform W0 with a peak magnitude of the combined waveform. For example, instead of increasing the phase ϕ_{W5} of the combined waveform W5 by the phase difference ϕ_{W5W0} , a phase of a combined waveform (not shown) is decreased by a phase difference between a peak magnitude of the fundamental waveform W0 and a peak magnitude of the combined waveform (not shown) to align a peak magnitude of the fundamental waveform W0 with a peak magnitude of the combined waveform (not shown).

[0032] Similarly, a combined waveform W3, which is a sum of the fundamental waveform W0 and a fifth harmonic waveform of the fundamental waveform W0, is plotted. The combined waveform W3 has a phase of $\pi/4$ relative to a phase of the fundamental waveform W0.

[0033] Also, the combined waveform W3 is generated when plasma is generated within a plasma chamber, which may be the same or different from the plasma chamber that in which the combined waveform W5 is generated.

[0034] The fundamental waveform W0 is extracted from the combined waveform W3 in a similar manner in which the fundamental waveform W0 is extracted from the combined waveform W5.

[0035] A difference in a peak magnitude $W3_{mag}$ of the combined waveform W3 and a peak magnitude $W0_{mag}$ of the fundamental waveform W0 is determined. The peak

[0039] In various embodiments, the combined waveform W3 is generated when power is supplied to the plasma chamber 1 and the combined waveform W5 is generated when power is supplied to a plasma chamber 2. In some embodiments, the plasma chamber 2 has the same structure as that of the plasma chamber 1. For example, the plasma chamber 2 includes elements that have same dimensions as that of corresponding elements in the plasma chamber 1. As another example, the plasma chamber 2 includes elements that are of the same type as that of corresponding elements in the plasma chamber 1. To illustrate, a transformer coupled plasma (TCP) chamber is of a different type than an inductively coupled plasma (ICP) chamber and both the TCP and the ICP chambers are of different types than an electron cyclotron resonance (ECR) plasma chamber.

[0040] Examples of elements of a plasma chamber include an upper electrode, a lower electrode, an upper plasma exclusion zone (PEZ) ring, a lower PEZ ring, a heater, a confinement ring assembly, an edge ring, an insulator layer, gas distribution apertures, walls of the plasma chamber, an upper dielectric ring surrounding the upper electrode, an upper electrode extension surrounding the upper dielectric ring, a lower dielectric ring surrounding the lower electrode, a lower electrode extension surrounding the lower dielectric ring, etc. The lower electrode is made of a metal, e.g., anodized aluminum, alloy of aluminum, etc. Also, the upper electrode is made of a metal, e.g., aluminum, alloy of aluminum, etc. The upper electrode is located opposite to and facing the lower electrode.

[0041] Examples of dimensions of an element include a size of the element, a length of the element, a depth of the element, a width of the elements, a surface area of the element, a volume occupied by the element, etc.

[0042] Examples of elements of different types include a plate electrode, an electric coil electrode, etc.

[0043] In various embodiments, the plasma chamber 2 is structurally identical to plasma chamber 1 and has a different identification code than that of the plasma chamber 1. For example, an entity identifies the plasma chamber 1 using an identity code aaaa and the entity identifies the plasma chamber 2 using an identity code bbbb. Examples of an entity include a corporation, a partnership, etc.

[0044] In a number of embodiments, the plasma chamber 2 is structurally identical to the plasma chamber 1 and is used to perform the same function as that of the plasma chamber 1. Examples of a function performed by a plasma chamber include physical

vapor deposition (PVD), chemical vapor deposition (CVD), plasma-enhanced CVD (PECVD), metal CVD, a high-density plasma CVD (HDP-CVD) function, a photoresist strip function, a photoresist surface preparation, ultraviolet thermal processing (UVTP), etc.

[0045] In various embodiments, the plasma chamber 2 is structurally and functionally identical to plasma chamber 1 and has a different identification code than that of the plasma chamber 1.

[0046] In several embodiments, power is supplied to the plasma chamber 1, which is a golden chamber. In these embodiments, the plasma chamber 1 has a higher yield than that of the plasma chamber 2. When power is supplied to the plasma chamber 1, the combined waveform W3 is generated and the fundamental waveform W0 is extracted from the combined waveform W3. Also, in these embodiments, when power is supplied to the plasma chamber 2, the combined waveform W5 is generated. Moreover, power supplied to the plasma chamber 2 is adjusted to modify the peak magnitude W5mag of the combined waveform W5 to achieve the magnitude W0mag of the fundamental waveform that is generated using the plasma chamber 1.

[0047] In some embodiments, instead of adjusting the power supplied to the plasma chamber 2 to adjust the peak magnitude W5mag to match the peak magnitude W0mag, elements of a plasma system that includes the plasma chamber 2 are changed, e.g., replaced, tweaked, etc., to reduce the phase difference ϕ_{W5W0} . For example, a user changes an RF transmission line of the plasma chamber 2 to reduce the phase difference ϕ_{W5W0} . As another example, a user tweaks a distance between plates of a capacitor of an impedance matching circuit of the plasma chamber 2 to reduce the phase difference ϕ_{W5W0} .

[0048] Other examples of elements of a plasma system include an RF cable that couples an RF generator of the plasma system to an impedance matching circuit of the plasma system, an inductor of the impedance matching circuit, and an element of a plasma chamber of the plasma system.

[0049] In various embodiments, instead of changing elements of a plasma system randomly or sequentially, a scan, e.g., an impedance scan, a network scan, etc., is performed at one or more points between the x MHz RF generator and a wafer to determine an element that is to be changed. For example, an impedance scanner is coupled to an RF transmission line to generate impedance characteristics of elements of the plasma system between the RF transmission line and an end of the plasma system. It should be noted that in several

embodiments, a plasma chamber is located at an end of the plasma system and an RF generator is located at a beginning of the plasma system. Impedance characteristics may include a peak, which may be in phase with a phase of a harmonic waveform. Upon determining that the peak is in phase with a phase of the harmonic waveform, it is determined that an element that is to be changed lies between the impedance scanner and an output of the RF transmission line or within the plasma chamber. Upon determining that the peak is out of phase with a phase of the harmonic waveform, the impedance scanner is coupled to a matchbox coupled to the RF transmission line to determine whether an element of the plasma system that is to be changed is located between the impedance scanner and the end of the plasma system.

[0050] Also, in some embodiments, instead of the plasma chamber 1 being a golden chamber, the plasma chamber 2 is a golden chamber. For example, the plasma chamber 2 has a higher yield than the plasma chamber 1. In these embodiments, instead of using the plasma chamber 1 to generate the fundamental waveform W0, the plasma chamber 2 is used to generate the fundamental waveform W0. For example, power is supplied to the plasma chamber 2 to generate plasma within the plasma chamber 2. Voltage of the plasma is measured to generate the combined waveform W3. The fundamental waveform W0 is extracted from the combined waveform W3. Continuing with the example, when power is supplied to the plasma chamber 1, the combined waveform W5 is generated. Power supplied to the plasma chamber 1 is adjusted to modify the peak magnitude W5mag of the combined waveform W5 to achieve the peak magnitude W0mag of the fundamental waveform W0 that is generated based on the waveform W3 of the plasma chamber 2.

[0051] In some embodiments, instead of adjusting the power supplied to the plasma chamber 2 to adjust the peak magnitude W5mag to match the peak magnitude W0mag, one or more elements of a plasma system that includes the plasma chamber 2 are changed to reduce the phase difference ϕ_{W5W0} .

[0052] A plasma chamber has a higher yield than another plasma chamber when the higher yield plasma chamber is used to etch a wafer to achieve a higher aspect ratio than that achieved using the lower yield plasma chamber, when use of the higher yield plasma chamber results in wafers that are cleaner than those cleaned using the lower yield plasma chamber, when the higher yield plasma chamber etches at a faster rate than that achieved using the lower yield plasma chamber, when the higher yield plasma chamber cleans wafers at a faster rate than that achieved using the lower yield plasma chamber, when the higher

[0072] The DAS 132 receives the power values and the frequency and generates an RF signal having the power values and the frequency. The RF signal is supplied via an RF cable 134 to a matchbox 136, which is an impedance matching circuit.

[0073] In some embodiments, the DAS 132 amplifies an RF signal that is generated by a driver of the DAS to generate an amplified RF signal, which is supplied via the RF cable 134 to the matchbox 136.

[0074] In various embodiments, when an RF signal is generated by the x MHz RF generator, the y and z MHz RF generators do not generate RF signals. For example, the y and z MHz RF generators are turned off when the x MHz RF generator is used to generate an RF signal.

[0075] An impedance matching circuit includes electric circuit components, e.g., inductors, capacitors, etc. to match an impedance of a power source coupled to the impedance matching circuit with an impedance of a load coupled to the impedance matching circuit. For example, the matchbox 136 matches an impedance of a source, which includes the x, y, and z MHz RF generators, RF cables 134, 137, and 138 coupling the matchbox 136 to the x, y, and z MHz RF generators with an impedance of an RF transmission line 140 and the plasma chamber 122. An impedance match between a power source and a load reduces chances of power being reflected from the load towards the power source.

[0076] The RF transmission line 140 is coupled to the matchbox 136 and to the ESC 126 of the plasma chamber 122. The RF transmission line 140 includes an RF cable 142, which is coupled to an RF tunnel 144, and the RF tunnel 144 is coupled to an RF strap 148. Within the RF tunnel 144 lays an insulator 150 and an RF rod 152. The insulator 150 insulates the RF rod 152 from a sheath of the RF tunnel 144. The RF rod 152 is coupled via the connector 146 to the RF strap 148, which is sometimes also known as an RF spoon. The RF strap 148 is coupled to the lower electrode of the ESC 126.

[0077] A wafer 154, e.g., a semiconductor wafer, is supported on an upper surface 156 of the ESC 126. Integrated circuits, e.g., application specific integrated circuits (ASICs), programmable logic devices (PLDs), etc. are developed on the wafer 154 and the integrated circuits are used in a variety of devices, e.g., cell phones, tablets, smart phones, computers, laptops, networking equipment, etc. An upper electrode 158 faces the lower electrode of the ESC 126.

132 generates an RF signal having the power value and the RF signal is supplied via the RF cable 134, the matchbox 136, and the RF transmission line 140 to the lower electrode of the ESC 126 to achieve the peak magnitude $W0_{mag}$ of the fundamental waveform $W0$.

[0095] In several embodiments, a peak magnitude of a combined waveform is increased by the processor of the host system 128 to match the peak magnitude $W0_{mag}$ of the fundamental waveform $W0$.

[0096] In various embodiments, the processor of the host system 128 determines the phase difference $\phi W5W0$ between the phase $\phi W5$ of the combined waveform $W5$ and the phase $\phi W0$ of the fundamental waveform $W0$.

[0097] In some embodiments, a user changes one or more elements of the plasma system 120 to reduce the phase difference $\phi W5W0$. For example, a user replaces one or more of the RF cable 134, the matchbox 136, the RF cable 142, RF tunnel 144, and the RF strap 148 to eliminate the phase difference $\phi W5W0$. In this example, the user replaces the RF cable 134 with another RF cable, replaces the matchbox 136 with another matchbox, replaces the RF cable 142 with another RF cable, replaces the RF tunnel 144 with another RF tunnel, and/or replaces the RF strap 148 with another RF strap. As another example, a user tweaks spacing between capacitor plates of a capacitor within the matchbox 136 to eliminate the phase difference $\phi W5W0$.

[0098] In some embodiments, the user replaces an element with another element that has similar characteristics, e.g., inductance, capacitance, resistance, a combination thereof, etc., as that of the element that is replaced. For example, the RF cable that replaced the RF cable 134 has the same resistance as that of the RF cable 134. As another example, the matchbox that replaces the matchbox 136 has the same capacitance as that of the matchbox 136.

[0099] In several embodiments, the processor of the host system 128 is notified by a user of a change to one or more elements of the plasma system 120. For example, the user indicates to the processor via an input device that one or more of the RF cable 134, the matchbox 136, the RF cable 142, RF tunnel 144, and the RF strap 148 is replaced. As another example, the user indicates via the input device to the processor of the host system 128 that spacing between capacitor plates of a capacitor within the matchbox 136.

[00100] Examples of an input device include a keyboard, a mouse, a stylus, a trackball, etc. The input device is coupled to the processor of the host system 128.

of the RF strap 148. As yet another example, the ESC model 182 has the same capacitance, inductance, resistance, or a combination thereof as that of the ESC 127.

[00111] The processor 184 receives a measurement of the voltage from the probe 124 (Figure 3A). The processor 184 determines a value of the voltage variable at an output of the ESC model 182 based on the measurement of the voltage received from the probe 124 and the characteristics of the strap model 192 and the ESC model 182. For example, the processor 184 receives the current at the output of the RF rod 152 (Figure 3A), receives a magnitude of the voltage at the output of the RF rod 152, receives a phase of the voltage, and determines a directed sum of the voltage, and voltages generated by the capacitances, inductances, and/or resistances of the strap model 192 and the ESC model 182 to determine voltage and current at the output of the ESC model 182.

[00112] The processor 184 uses the voltage at the output of the ESC model 182 instead of the measurement of the voltage from the probe 124 to determine waveforms of voltages of plasma within the plasma chamber 123 (Figure 3A).

[00113] In various embodiments, the probe 124 is connected to an input of the RF rod 152 instead of to the output of the RF rod 152. In these embodiments, the processor 184 determines a voltage at an output of the ESC model 182 based on the measurement of the voltage received from the probe 124 and the characteristics of the tunnel model 190, the strap model 192 and the ESC model 182.

[00114] In some embodiments, instead of using the ESC model 182 in addition to the strap model 192, the processor 184 uses the strap model 192 to determine the voltage at the output of the strap model 192 and uses the voltage to determine waveforms of voltage of plasma within the plasma chamber 123 (Figure 3A). For example, the processor 184 determines a voltage at an output of the strap model 192 based on the measurement of the voltage received from the probe 124 and the characteristics of the strap model 192.

[00115] In various embodiments, the probe 124 is coupled to any point between the x MHz RF generator and the wafer 154 (Figure 3A). For example, the probe 124 is coupled to the RF cable 134. In these embodiments, a computer-generated model of elements of the plasma system 172 between the point and the wafer 154 is generated and voltage at a computer-generated model of the ESC 127 is determined based on the voltage measured with the probe 124 and impedances of elements between the point and the wafer 154. For example, when the probe 124 is coupled to a point on the RF cable 134, a computer-

transmission line 140 has the same resistance, inductance, capacitance, or a combination thereof as that of the RF transmission line 140.

[00133] In some embodiments, instead of using the probe 124 within the ESC 204, the probe 124 is embedded within the RF tunnel 144 or is coupled to the RF rod 152 to measure voltage at the RF rod 152. A computer-generated model of the RF rod 152, the RF strap 148, and the ESC 204 is used to determine voltage at the ESC 204. The voltage at the ESC 204 is determined based on the voltage measured using the probe 124 that is embedded within the RF tunnel ~~144~~¹⁵⁵ and impedance of elements of the RF rod 152, the RF strap ~~148~~¹⁵², and the ESC 204. In several embodiments, instead of using a computer-generated model of the ESC 204, voltage at the ESC 204 is determined based on a computer-generated model of the RF rod 152 and the RF strap 148 and based on the voltage measured using the probe 124 that is embedded within the RF tunnel ~~144~~¹⁵⁵.

[00134] In some embodiments, the probe 124 is coupled to a point between the x MHz RF generator and the wafer 154 and a computer-generated model of elements between the point and the plasma chamber 204 is used to determine a voltage at the ESC 204. For example, the probe 124 is coupled to the RF cable 134 to determine voltage at the RF cable 134. Moreover, a computer-generated model of the matchbox 136, the RF transmission line 140, and the ESC 204 is used to determine a voltage at the ESC 204. As another example, the probe 124 is coupled to the RF cable 134 to determine voltage at the RF cable 134. Moreover, a computer-generated model of the matchbox 136 and the RF transmission line 140 is used to determine a voltage at the ESC 204.

[00135] It should be noted that in several embodiments, when the x MHz RF generator of the system 200 is used to supply power to the plasma chamber 202 to determine a combined waveform, the y and z MHz RF generators are turned off. Similarly, when the y MHz RF generator of the system 200 is used to supply power to the plasma chamber 202 to determine a combined waveform, the x and z MHz RF generators are turned off. Also, when the z MHz RF generator of the system 200 is used to supply power to the plasma chamber 202 to determine a combined waveform, the y and z MHz RF generators are turned off.

[00136] In several embodiments, the processor of the host system 128 is notified by a user of a change to one or more elements of the plasma system 200. For example, the user indicates to the processor via the input device that one or more of the RF cable 134, the matchbox 136, the RF cable 142, RF tunnel 144, and the RF strap 148 is replaced. As

13. A method for compensating for harmonics produced during plasma processing in a plasma chamber, the method comprising:

retrieving a measurement of a combined waveform, the combined waveform including a fundamental waveform and a harmonic waveform, the combined waveform defining a voltage proximate to a surface of a chuck, the chuck coupled to a radio frequency (RF) transmission line, the RF transmission line coupled to an impedance matching circuit, the impedance matching circuit coupled to an RF generator;

extracting the fundamental waveform from the combined waveform;

determining a difference between a phase of the combined waveform and a phase of the fundamental waveform; and

receiving an indication of a change to a plasma system, the change made to compensate for the difference, the plasma system including the RF transmission line, an RF cable coupling the impedance matching circuit to the RF generator, the impedance matching circuit, or a combination thereof,

wherein the method is executed by one or more processors.

14. The method of claim 13, wherein the change to the plasma system comprises:

a replacement of the RF transmission line with another RF transmission line;

a replacement of the RF cable with another RF cable;

a replacement of the impedance matching circuit with another matching circuit; or
a combination thereof.

15. A method for performing chamber-to-chamber matching, the method comprising:

retrieving a measurement of a combined waveform, the combined waveform including a fundamental waveform and a harmonic waveform, the combined waveform defining a voltage proximate to a surface of a chuck, the chuck coupled to a radio frequency (RF) transmission line, the RF transmission line coupled to an impedance matching circuit, the impedance matching circuit coupled to an RF generator;

extracting the fundamental waveform from the combined waveform;

receiving an indication of coupling another chuck to the RF transmission line;

retrieving a measurement of another combined waveform, the other combined waveform defining a voltage proximate to a surface of the other chuck;

determining a difference between a magnitude of the other combined waveform and a magnitude of the fundamental waveform; and