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USING MODELING TO DETERMINE WAFER BIAS ASSOCIATED WITH A PLASMA SYSTEM

Field

[0001] The present embodiments relate to using modeling to determine wafer bias associated with a plasma system.

Background

[0002] In a plasma-based system, plasma is generated within a plasma chamber to perform various operations, e.g., etching, cleaning, depositing, etc., on a wafer. The plasma is monitored and controlled to control performance of the various operations. For example, the plasma is monitored by monitoring a voltage of the plasma and is controlled by controlling an amount of radio frequency (RF) power supplied to the plasma chamber.

[0003] However, the use of voltage to monitor and control the performance of the operations may not provide satisfactory results. Moreover, the monitoring of voltage may be an expensive and time consuming operation.

[0004] It is in this context that embodiments described in the present disclosure arise.

Summary

[0005] Embodiments of the disclosure provide apparatus, methods and computer programs for using modeling to determine wafer bias associated with a plasma system. It should be appreciated that the present embodiments can be implemented in numerous ways, e.g., a process, an apparatus, a system, a piece of hardware, or a method on a computer-readable medium. Several embodiments are described below.

[0006] In various embodiments, wafer bias is determined at a model node of a model. The model may be a model of a radio frequency (RF) transmission line, an impedance matching circuit, or of an electrostatic chuck (ESC). The model node of the model may be an input, an output, or a point within the model. The wafer bias at the model node is determined by propagating a complex voltage and current from an output of an RF



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generator to the model node to determine a complex voltage and current at the model node. The complex voltage and current at the output of the RF generator is measured with a voltage and current probe that is calibrated according to a pre-set formula. In some embodiments, the wafer bias at the model node is a sum of a product of a coefficient and a voltage magnitude at the model node, a product of a coefficient and a current magnitude at the model node, a product of a coefficient and a square root of a power magnitude at the model node, and a constant.

[0007] In some embodiments, a method for determining wafer bias is described. The method includes detecting output of a generator to identify a generator output complex voltage and current (V&I). The generator is coupled to an impedance matching circuit and the impedance matching circuit is coupled via a radio frequency (RF) transmission line to an electrostatic chuck (ESC) of a plasma chamber. The method further includes determining from the generator output complex V&I a projected complex V&I at a point along a path between an output of a model of the impedance matching circuit and a model of the ESC. The operation of determining of the projected complex V&I performed using a model for at least part of the path. The model for at least part of the path characterizes physical components along the path. The method includes applying the projected complex V&I as an input to a function to map the projected complex V&I to a wafer bias value at the ESC model.

[0008] In various embodiments, a method for determining wafer bias is described. The method includes receiving one or more generator output complex voltages and currents measured at one or more outputs of one or more generators. The one or more generators are coupled to an impedance matching circuit, which is coupled via a radio frequency (RF) transmission line to an electrostatic chuck (ESC) of a plasma chamber. The method further includes determining from the one or more complex voltages and currents projected complex voltage and current at a point along a path between a model of the impedance matching circuit and a model of the ESC. The models characterize physical components along the path. The method includes calculating a wafer bias at the point by using the projected complex voltage and current as an input to a function.

[0009] In several embodiments, a method for determining wafer bias is described. The method includes identifying a first complex voltage and current measured at an output of a radio frequency (RF) generator when the RF generator is coupled to a plasma chamber via an impedance matching circuit. The impedance matching circuit has an input coupled to the

output of the RF generator and an output coupled to an RF transmission line. The method further includes generating an impedance matching model based on electrical components defined in the impedance matching circuit. The impedance matching model has an input and an output. The input of the impedance matching model receives the first complex voltage and current. The impedance matching model also has one or more elements. The method includes propagating the first complex voltage and current through the one or more elements from the input of the impedance matching model to the output of the impedance matching model to determine a second complex voltage and current. The second complex voltage and current is at the output of the impedance matching model. The method includes determining a wafer bias based on a voltage magnitude of the second complex voltage and current, a current magnitude of the second complex voltage and current, and a power magnitude of the second complex voltage and current.

[0010] In some embodiments, a plasma system for determining wafer bias is described. The plasma system includes one or more radio frequency (RF) generators for generating one or more RF signals. The one or more RF generators are associated with one or more voltage and current probes. The one or more voltage and current probes are configured to measure one or more complex voltages and currents at corresponding one or more outputs of the one or more RF generators. The plasma system further includes an impedance matching circuit coupled to the one or more RF generators. The plasma system also includes a plasma chamber coupled to the impedance matching circuit via an RF transmission line. The plasma chamber includes an electrostatic chuck (ESC), which is coupled to the RF transmission line. The plasma system includes a processor coupled to the one or more RF generators. The processor is configured to receive the one or more complex voltages and currents and determine from the one or more complex voltages and currents projected complex voltage and current at a point along a path between a model of the impedance matching circuit and a model of the ESC. The models characterize physical components along the path. The processor is configured to calculate a wafer bias at the point by using the projected complex voltage and current as an input to a function.

[0011] Some advantages of the above-described embodiments include determining the wafer bias without a need to couple a voltage probe to a point, e.g., a node on the RF transmission line, an output of the impedance matching circuit, a point on the ESC, etc. In some systems, the voltage probe measures voltage at the point and the measured voltage is used to determine bias at the ESC. The voltage probe is expensive to obtain.

Moreover, a module that determines whether the measured voltage is a signal or noise is implemented within the plasma system when the voltage probe is used. Upon determining that the measured voltage is a signal, the voltage is used to control RF power delivered to a plasma chamber of the plasma system to compensate for the bias at the ESC. On the other hand, upon determining that the voltage is noise, the voltage is not used to control the RF power. The determination by the module is costly and time consuming. Comparatively, the wafer bias is determined without a need to couple the voltage probe to the point. The nonuse of the voltage probe saves costs associated with the voltage probe and time and effort associated with the module. Also, the voltage probe may malfunction or may be unable to operate during manufacturing, processing, cleaning, etc. of a substrate. The voltage and current probe complies with the pre-set formula and is more accurate than that of the voltage probe. Also, the wafer bias is determined based on the complex voltage and current measured with the voltage and current probe. The complex voltage and current measured and used provides a better accuracy of wafer bias than the ESC bias that is determined based on voltage measured by the voltage probe.

[0012] Other aspects will become apparent from the following detailed description, taken in conjunction with the accompanying drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

[0013] The embodiments may best be understood by reference to the following description taken in conjunction with the accompanying drawings.

[0014] Figure 1 is a block diagram of a system for determining a variable at an output of an impedance matching model, at an output of a portion of a radio frequency (RF) transmission model, and at an output of an electrostatic chuck (ESC) model, in accordance with an embodiment described in the present disclosure.

[0015] Figure 2 is a flowchart of a method for determining a complex voltage and current at the output of the RF transmission model portion, in accordance with an embodiment described in the present disclosure.

[0016] Figure 3A is a block diagram of a system used to illustrate an impedance matching circuit, in accordance with an embodiment described in the present disclosure.

[0017] Figure 3B is a circuit diagram of an impedance matching model, in accordance with an embodiment described in the present disclosure.

[0018] Figure 4 is a diagram of a system used to illustrate an RF transmission line, in accordance with an embodiment described in the present disclosure.

[0019] Figure 5A is a block diagram of a system used to illustrate a circuit model of the RF transmission line, in accordance with an embodiment described in the present disclosure.

[0020] Figure 5B is a diagram of an electrical circuit used to illustrate a tunnel and strap model of the RF transmission model, in accordance with an embodiment described in the present disclosure.

[0021] Figure 5C is a diagram of an electrical circuit used to illustrate a tunnel and strap model, in accordance with an embodiment described in the present disclosure.

[0022] Figure 6 is a diagram of an electrical circuit used to illustrate a cylinder and ESC model, in accordance with an embodiment described in the present disclosure.

[0023] Figure 7 is a block diagram of a plasma system that includes filters used to determine the variable, in accordance with an embodiment described in the present disclosure.

[0024] Figure 8A is a diagram of a system used to illustrate a model of the filters to improve an accuracy of the variable, in accordance with an embodiment described in the present disclosure.

[0025] Figure 8B is a diagram of a system used to illustrate a model of the filters, in accordance with an embodiment described in the present disclosure.

[0026] Figure 9 is a block diagram of a system for using a current and voltage probe to measure the variable at an output of an RF generator of the system of Figure 1, in accordance with one embodiment described in the present disclosure.

[0027] Figure 10 is a block diagram of a system in which the voltage and current probe and a communication device are located outside the RF generator, in accordance with an embodiment described in the present disclosure.

[0028] Figure 11 is a block diagram of a system in which values of the variable determined using the system of Figure 1 are used, in accordance with an embodiment described in the present disclosure.

[0029] Figure 12A is a diagram of a graph that illustrates a correlation between a variable that is measured at a node within the system of Figure 1 by using a probe and a variable that is determined using the method of Figure 2 when an x MHz RF generator is on, in accordance with an embodiment described in the present disclosure.

[0030] Figure 12B is a diagram of a graph that illustrates a correlation between a variable that is measured at a node within the system of Figure 1 by using a probe and a variable that is determined using the method of Figure 2 when a y MHz RF generator is on, in accordance with an embodiment described in the present disclosure.

[0031] Figure 12C is a diagram of a graph that illustrates a correlation between a variable that is measured at a node within the system of Figure 1 by using a probe and a variable that is determined using the method of Figure 2 when a z MHz RF generator is on, in accordance with one embodiment described in the present disclosure.

[0032] Figure 13 is a flowchart of a method for determining wafer bias at a model node of the impedance matching model, the RF transmission model, or the ESC model, in accordance with an embodiment described in the present disclosure.

[0033] Figure 14 is a state diagram illustrating a wafer bias generator used to generate a wafer bias, in accordance with an embodiment described in the present disclosure.

[0034] Figure 15 is a flowchart of a method for determining a wafer bias at a point along a path between the impedance matching model and the ESC model, in accordance with an embodiment described in the present disclosure.

[0035] Figure 16 is a block diagram of a system for determining a wafer bias at a node of a model, in accordance with an embodiment described in the present disclosure.

[0036] Figure 17 is a flowchart of a method for determining a wafer bias at a model node of the system of Figure 1, in accordance with an embodiment described in the present disclosure.

[0037] Figure 18 is a block diagram of a system that is used to illustrate advantages of determining wafer bias by using the method of Figure 13, Figure 15, or Figure 17 instead of by using a voltage probe, in accordance with an embodiment described in the present disclosure.

[0038] Figure 19A show embodiments of graphs to illustrate a correlation between a variable that is measured at a node of the plasma system of Figure 1 by using a voltage probe and a variable at a corresponding model node output determined using the method of Figure 2, 13, 15, or 17 when the y and z MHz RF generators are on, in accordance with an embodiment described in the present disclosure.

[0039] Figure 19B show embodiments of graphs to illustrate a correlation between a variable that is measured at a node of the plasma system of Figure 1 by using a voltage probe and a variable at a corresponding model node output determined using the method of Figure 2, 13, 15, or 17 when the x and z MHz RF generators are on, in accordance with an embodiment described in the present disclosure.

[0040] Figure 19C show embodiments of graphs to illustrate a correlation between a variable that is measured at a node of the plasma system of Figure 1 by using a voltage probe and a variable at a corresponding model node output determined using the method of Figure 2, 13, 15, or 17 when the x and y MHz RF generators are on, in accordance with an embodiment described in the present disclosure.

[0041] Figure 20A is a diagram of graphs used to illustrate a correlation between a wired wafer bias measured using a sensor tool, a model wafer bias that is determined using the method of Figure 13, 15, or 17 and an error in the model bias when the x MHz RF generator is on, in accordance with an embodiment described in the present disclosure.

[0042] Figure 20B is a diagram of graphs used to illustrate a correlation between a wired wafer bias measured using a sensor tool, a model bias that is determined using the method of Figure 13, 15, or 17 and an error in the model bias when the y MHz RF generator is on, in accordance with one embodiment described in the present disclosure.

[0043] Figure 20C is a diagram of embodiments of graphs used to illustrate a correlation between a wired wafer bias measured using a sensor tool, a model bias that is determined using the method of Figure 13, 15, or 17 and an error in the model bias when the z MHz RF generator is on, in accordance with one embodiment described in the present disclosure.

[0044] Figure 20D is a diagram of graphs used to illustrate a correlation between a wired wafer bias measured using a sensor tool, a model bias that is determined using the method of Figure 13, 15, or 17 and an error in the model bias when the x and y MHz RF generators are on, in accordance with an embodiment described in the present disclosure.

[0045] Figure 20E is a diagram of graphs used to illustrate a correlation between a wired wafer bias measured using a sensor tool, a model bias that is determined using the method of Figure 13, 15, or 17 and an error in the model bias when the x and z MHz RF generators are on, in accordance with an embodiment described in the present disclosure.

[0046] Figure 20F is a diagram of graphs used to illustrate a correlation between a wired wafer bias measured using a sensor tool, a model bias that is determined using the method of Figure 13, 15, or 17 and an error in the model bias when the y and z MHz RF generators are on, in accordance with an embodiment described in the present disclosure.

[0047] Figure 20G is a diagram of graphs used to illustrate a correlation between a wired wafer bias measured using a sensor tool, a model bias that is determined using the method of Figure 13, 15, or 17 and an error in the model bias when the x, y, and z MHz RF generators are on, in accordance with an embodiment described in the present disclosure.

[0048] Figure 21 is a block diagram of a host system of the system of Figure 1, in accordance with an embodiment described in the present disclosure.

DETAILED DESCRIPTION

[0049] The following embodiments describe systems and methods for using a model to determine a wafer bias associated with a plasma system. 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.

[0050] Figure 1 is a block diagram of an embodiment of a system 126 for determining a variable at an output of an impedance matching model 104, at an output, e.g., a model node N1m, of a portion 173 of an RF transmission model 161, which is a model of an RF transmission line 113, and at an output, e.g., a model node N6m, of an electrostatic chuck (ESC) model 125. Examples of a variable include complex voltage, complex current, complex voltage and current, complex power, wafer bias, etc. The RF transmission line 113 has an output, e.g., a node N2. A voltage and current (VI) probe 110 measures a complex voltage and current V_x , I_x , and ϕ_x , e.g., a first complex voltage and current, at an output, e.g., a node N3, of an x MHz RF generator. It should be noted that V_x represents a voltage magnitude, I_x represents a current magnitude, and ϕ_x represents a phase between V_x and I_x . The impedance matching model 104 has an output, e.g., a model node N4m.

[0051] Moreover, a voltage and current probe 111 measures a complex voltage and current V_y , I_y , and ϕ_y at an output, e.g., a node N5, of a y MHz RF generator. It should be noted that V_y represents a voltage magnitude, I_y represents a current magnitude, and ϕ_y represents a phase between V_y and I_y .

[0052] In some embodiments, a node is an input of a device, an output of a device, or a point within the device. A device, as used herein, is described below.

[0053] Examples of x MHz include 2 MHz, 27 MHz, and 60 MHz. Examples of y MHz include 2 MHz, 27 MHz, and 60 MHz. The x MHz is different than y MHz. For example, when x MHz is 2 MHz, y MHz is 27 MHz or 60 MHz. When x MHz is 27 MHz, y MHz is 60 MHz.

[0054] An example of each voltage and current probe 110 and 111 includes a voltage and current probe that complies with a pre-set formula. An example of the pre-set formula includes a standard that is followed by an Association, which develops standards for sensors. Another example of the pre-set formula includes a National Institute of Standards and Technology (NIST) standard. As an illustration, the voltage and current probe 110 or

111 is calibrated according to NIST standard. In this illustration, the voltage and current probe 110 or 111 is coupled with an open circuit, a short circuit, or a known load to calibrate the voltage and current probe 110 or 111 to comply with the NIST standard. The voltage and current probe 110 or 111 may first be coupled with the open circuit, then with the short circuit, and then with the known load to calibrate the voltage and current probe 110 based on NIST standard. The voltage and current probe 110 or 111 may be coupled to the known load, the open circuit, and the short circuit in any order to calibrate the voltage and current probe 110 or 111 according to NIST standard. Examples of a known load include a 50 ohm load, a 100 ohm load, a 200 ohm load, a static load, a direct current (DC) load, a resistor, etc. As an illustration, each voltage and current probe 110 and 111 is calibrated according NIST-traceable standards.

[0055] The voltage and current probe 110 is coupled to the output, e.g., the node N3, of the x MHz RF generator. The output, e.g., the node N3, of the x MHz RF generator is coupled to an input 153 of an impedance matching circuit 114 via a cable 150. Moreover, the voltage and current probe 111 is coupled to the output, e.g., the node N5, of the y MHz RF generator. The output, e.g., the node N5, of the y MHz RF generator is coupled to another input 155 of the impedance matching circuit 114 via a cable 152.

[0056] An output, e.g., a node N4, of the impedance matching circuit 114 is coupled to an input of the RF transmission line 113. The RF transmission line 113 includes a portion 169 and another portion 195. An input of the portion 169 is an input of the RF transmission line 113. An output, e.g., a node N1, of the portion 169 is coupled to an input of the portion 195. An output, e.g., the node N2, of the portion 195 is coupled to the plasma chamber 175. The output of the portion 195 is the output of the RF transmission line 113. An example of the portion 169 includes an RF cylinder and an RF strap. The RF cylinder is coupled to the RF strap. An example of the portion 195 includes an RF rod and/or a support, e.g., a cylinder, etc., for supporting the plasma chamber 175.

[0057] The plasma chamber 175 includes an electrostatic chuck (ESC) 177, an upper electrode 179, and other parts (not shown), e.g., an upper dielectric ring surrounding the upper electrode 179, an upper electrode extension surrounding the upper dielectric ring, a lower dielectric ring surrounding a lower electrode of the ESC 177, a lower electrode extension surrounding the lower dielectric ring, an upper plasma exclusion zone (PEZ) ring, a lower PEZ ring, etc. The upper electrode 179 is located opposite to and facing the ESC 177. A work piece 131, e.g., a semiconductor wafer, etc., is supported on an upper surface 183 of

the ESC 177. The upper surface 183 includes an output N6 of the ESC 177. The work piece 131 is placed on the output N6. Various processes, e.g., chemical vapor deposition, cleaning, deposition, sputtering, etching, ion implantation, resist stripping, etc., are performed on the work piece 131 during production. Integrated circuits, e.g., application specific integrated circuit (ASIC), programmable logic device (PLD), etc. are developed on the work piece 131 and the integrated circuits are used in a variety of electronic items, e.g., cell phones, tablets, smart phones, computers, laptops, networking equipment, etc. Each of the lower electrode and the upper electrode 179 is made of a metal, e.g., aluminum, alloy of aluminum, copper, etc.

[0058] In one embodiment, the upper electrode 179 includes a hole that is coupled to a central gas feed (not shown). The central gas feed receives one or more process gases from a gas supply (not shown). Examples of a process gases include an oxygen-containing gas, such as O₂. Other examples of a process gas include a fluorine-containing gas, e.g., tetrafluoromethane (CF₄), sulfur hexafluoride (SF₆), hexafluoroethane (C₂F₆), etc. The upper electrode 179 is grounded. The ESC 177 is coupled to the x MHz RF generator and the y MHz RF generator via the impedance matching circuit 114.

[0059] When the process gas is supplied between the upper electrode 179 and the ESC 177 and when the x MHz RF generator and/or the y MHz RF generator supplies RF signals via the impedance matching circuit 114 and the RF transmission line 113 to the ESC 177, the process gas is ignited to generate plasma within the plasma chamber 175.

[0060] When the x MHz RF generator generates and provides an RF signal via the node N3, the impedance matching circuit 114, and the RF transmission line 113 to the ESC 177 and when the y MHz generator generates and provides an RF signal via the node N5, the impedance matching circuit 114, and the RF transmission line 113 to the ESC 177, the voltage and current probe 110 measures the complex voltage and current at the node N3 and the voltage and current probe 111 measures the complex voltage and current at the node N5.

[0061] The complex voltages and currents measured by the voltage and current probes 110 and 111 are provided via corresponding communication devices 185 and 189 from the corresponding voltage and current probes 110 and 111 to a storage hardware unit (HU) 162 of a host system 130 for storage. For example, the complex voltage and current measured by the voltage and current probe 110 is provided via the communication device 185 and a cable 191 to the host system 130 and the complex voltage and current measured by the

voltage and current probe 111 is provided via the communication device 189 and a cable 193 to the host system 130. Examples of a communication device include an Ethernet device that converts data into Ethernet packets and converts Ethernet packets into data, an Ethernet for Control Automation Technology (EtherCAT) device, a serial interface device that transfers data in series, a parallel interface device that transfers data in parallel, a Universal Serial Bus (USB) interface device, etc.

[0062] Examples of the host system 130 include a computer, e.g., a desktop, a laptop, a tablet, etc. As an illustration, the host system 130 includes a processor and the storage HU 162. As used herein, a processor may be a central processing unit (CPU), a microprocessor, an application specific integrated circuit (ASIC), a programmable logic device (PLD), etc. Examples of the storage HU include a read-only memory (ROM), a random access memory (RAM), or a combination thereof. The storage HU may be a flash memory, a redundant array of storage disks (RAID), a hard disk, etc.

[0063] The impedance matching model 104 is stored within the storage HU 162. The impedance matching model 104 has similar characteristics, e.g., capacitances, inductances, complex power, complex voltage and currents, etc., as that of the impedance matching circuit 114. For example, the impedance matching model 104 has the same number of capacitors and/or inductors as that within the impedance matching circuit 114, and the capacitors and/or inductors are connected with each other in the same manner, e.g., serial, parallel, etc. as that within the impedance matching circuit 114. To provide an illustration, when the impedance matching circuit 114 includes a capacitor coupled in series with an inductor, the impedance matching model 104 also includes the capacitor coupled in series with the inductor.

[0064] As an example, the impedance matching circuit 114 includes one or more electrical components and the impedance matching model 104 includes a design, e.g., a computer-generated model, of the impedance matching circuit 114. The computer-generated model may be generated by a processor based upon input signals received from a user via an input hardware unit. The input signals include signals regarding which electrical components, e.g., capacitors, inductors, etc., to include in a model and a manner, e.g., series, parallel, etc., of coupling the electrical components with each other. As another example, the impedance circuit 114 includes hardware electrical components and hardware connections between the electrical components and the impedance matching model 104 include software representations of the hardware electrical components and of the hardware connections. As

yet another example, the impedance matching model 104 is designed using a software program and the impedance matching circuit 114 is made on a printed circuit board. As used herein, electrical components may include resistors, capacitors, inductors, connections between the resistors, connections between the inductors, connections between the capacitors, and/or connections between a combination of the resistors, inductors, and capacitors.

[0065] Similarly, a cable model 163 and the cable 150 have similar characteristics, and a cable model 165 and the cable 152 has similar characteristics. As an example, an inductance of the cable model 163 is the same as an inductance of the cable 150. As another example, the cable model 163 is a computer-generated model of the cable 150 and the cable model 165 is a computer-generated model of the cable 152.

[0066] Similarly, an RF transmission model 161 and the RF transmission line 113 have similar characteristics. For example, the RF transmission model 161 has the same number of resistors, capacitors and/or inductors as that within the RF transmission line 113, and the resistors, capacitors and/or inductors are connected with each other in the same manner, e.g., serial, parallel, etc. as that within the RF transmission line 113. To further illustrate, when the RF transmission line 113 includes a capacitor coupled in parallel with an inductor, the RF transmission model 161 also includes the capacitor coupled in parallel with the inductor. As yet another example, the RF transmission line 113 includes one or more electrical components and the RF transmission model 161 includes a design, e.g., a computer-generated model, of the RF transmission line 113.

[0067] In some embodiments, the RF transmission model 161 is a computer-generated impedance transformation involving computation of characteristics, e.g., capacitances, resistances, inductances, a combination thereof, etc., of elements, e.g., capacitors, inductors, resistors, a combination thereof, etc., and determination of connections, e.g., series, parallel, etc., between the elements.

[0068] Based on the complex voltage and current received from the voltage and current probe 110 via the cable 191 and characteristics, e.g., capacitances, inductances, etc., of elements, e.g., inductors, capacitors, etc., within the impedance matching model 104, the processor of the host system 130 calculates a complex voltage and current V , I , and ϕ , e.g., a second complex voltage and current, at the output, e.g., the model node $N4m$, of the impedance matching model 104. The complex voltage and current at the model node $N4m$ is stored in the storage HU 162 and/or another storage HU, e.g., a compact disc, a flash

memory, etc., of the host system 130. The complex V , I , and ϕ includes a voltage magnitude V , a current magnitude I , and a phase ϕ between the voltage and current.

[0069] The output of the impedance matching model 104 is coupled to an input of the RF transmission model 161, which is stored in the storage hardware unit 162. The impedance matching model 104 also has an input, e.g., a node $N3m$, which is used to receive the complex voltage and current measured at the node $N3$.

[0070] The RF transmission model 161 includes the portion 173, another portion 197, and an output $N2m$, which is coupled via the ESC model 125 to the model node $N6m$. The ESC model 125 is a model of the ESC 177. For example, the ESC model 125 has similar characteristics as that of the ESC 177. For example, the ESC model 125 has the same inductance, capacitance, resistance, or a combination thereof as that of the ESC 177.

[0071] An input of the portion 173 is the input of the RF transmission model 161. An output of the portion 173 is coupled to an input of the portion 197. The portion 172 has similar characteristics as that of the portion 169 and the portion 197 has similar characteristics as that of the portion 195.

[0072] Based on the complex voltage and current measured at the model node $N4m$, the processor of the host system 130 calculates a complex voltage and current V , I , and ϕ , e.g., a third complex voltage and current, at the output, e.g., the model node $N1m$, of the portion 173 of the RF transmission model 161. The complex voltage and current determined at the model node $N1m$ is stored in the storage HU 162 and/or another storage HU, e.g., a compact disc, a flash memory, etc., of the host system 130.

[0073] In several embodiments, instead of or in addition to determining the third complex voltage and current, the processor of the host system 130 computes a complex voltage and current, e.g., an intermediate complex voltage and current V , I , and ϕ , at a point, e.g., a node, etc., within the portion 173 based on the complex voltage and current at the output of the impedance matching model 104 and characteristics of elements between the input of the RF transmission model 161 and the point within the portion 173.

[0074] In various embodiments, instead of or in addition to determining the third complex voltage and current, the processor of the host system 130 computes a complex voltage and current, e.g., an intermediate complex voltage and current V , I , and ϕ , at a point, e.g., a node, etc., within the portion 197 based on the complex voltage and current at the

output of the impedance matching model 104 and characteristics of elements between the input of the RF transmission model 161 and the point within the portion 197.

[0075] It should be noted that in some embodiments, the complex voltage and current at the output of the impedance matching model 104 is calculated based on the complex voltage and current at the output of the x MHz RF generator, characteristics of elements the cable model 163, and characteristics of the impedance matching model 104.

[0076] It should further be noted that although two generators are shown coupled to the impedance matching circuit 114, in one embodiment, any number of RF generators, e.g., a single generator, three generators, etc., are coupled to the plasma chamber 175 via an impedance matching circuit. For example, a 2 MHz generator, a 27 MHz generator, and a 60 MHz generator may be coupled to the plasma chamber 175 via an impedance matching circuit. For example, although the above-described embodiments are described with respect to using complex voltage and current measured at the node N3, in various embodiments, the above-described embodiments may also use the complex voltage and current measured at the node N5.

[0077] Figure 2 is a flowchart of an embodiment of a method 102 for determining the complex voltage and current at the output of the RF transmission model portion 173 (Figure 1). The method 102 is executed by the processor of the host system 130 (Figure 1). In an operation 106, the complex voltage and current, e.g., the first complex voltage and current, measured at the node N3 is identified from within the storage HU 162 (Figure 1). For example, it is determined that the first complex voltage and current is received from the voltage and current probe 110 (Figure 1). As another example, based on an identity, of the voltage and current probe 110, stored within the storage HU 162 (Figure 1), it is determined that the first complex voltage and current is associated with the identity.

[0078] Furthermore, in an operation 107, the impedance matching model 104 (Figure 1) is generated based on electrical components of the impedance matching circuit 114 (Figure 1). For example, connections between electrical components of the impedance matching circuit 114 and characteristics of the electrical components are provided to the processor of the host system 130 by the user via an input hardware unit that is coupled with the host system 130. Upon receiving the connections and the characteristics, the processor generates elements that have the same characteristics as that of electrical components of the

impedance matching circuit 114 and generates connections between the elements that have the same connections as that between the electrical components.

[0079] The input, e.g., the node N3m, of the impedance matching model 163 receives the first complex voltage and current. For example, the processor of the host system 130 accesses, e.g., reads, etc., from the storage HU 162 the first complex voltage and current and provides the first complex voltage and current to the input of the impedance matching model 104 to process the first complex voltage and current.

[0080] In an operation 116, the first complex voltage and current is propagated through one or more elements of the impedance matching model 104 (Figure 1) from the input, e.g., the node N3m (Figure 1), of the impedance matching model 104 to the output, e.g., the node N4m (Figure 1), of the impedance matching model 104 to determine the second complex voltage and current, which is at the output of the impedance matching model 104. For example, with reference to Figure 3B, when the 2 MHz RF generator is on, e.g., operational, powered on, coupled to the devices, such as, for example, the impedance matching circuit 104, of the plasma system 126, etc., a complex voltage and current V_{x1} , I_{x1} , and ϕ_{x1} , e.g., an intermediate complex voltage and current, which includes the voltage magnitude V_{x1} , the current magnitude I_{x1} , and the phase ϕ_{x1} between the complex voltage and current, at a node 251, e.g., an intermediate node, is determined based on a capacitance of a capacitor 253, based on a capacitance of a capacitor C5, and based on the first complex voltage and current that is received at an input 255. Moreover, a complex voltage and current V_{x2} , I_{x2} , and ϕ_{x2} at a node 257 is determined based on the complex voltage and current V_{x1} , I_{x1} , and ϕ_{x1} , and based on an inductance of an inductor L3. The complex voltage and current V_{x2} , I_{x2} , and ϕ_{x2} includes the voltage magnitude V_{x2} , the current magnitude I_{x2} , and the phase ϕ_{x2} between the voltage and current. When the 27 MHz RF generator and the 60 MHz RF generator are off, e.g., nonoperational, powered off, decoupled from the impedance matching circuit 104, etc., a complex voltage and current V2, I2, and ϕ_2 is determined to be the second complex voltage and current at an output 259, which is an example of the output, e.g., the model node N4m (Figure 1), of the impedance matching model 104 (Figure 1). The complex voltage and current V2, I2, and ϕ_2 is determined based on the complex voltage and current V_{x2} , I_{x2} , and ϕ_{x2} and an inductor of an inductor L2. The complex voltage and current V2, I2, and ϕ_2 includes the voltage magnitude V2, the current magnitude I2, and the phase ϕ_2 between the voltage and current.

[0081] Similarly, when 27 MHz RF generator is on and the 2 MHz and the 60 MHz RF generators are off, a complex voltage and current V_{27} , I_{27} , and ϕ_{27} at the output 259 is determined based on a complex voltage and current received at a node 261 and characteristics of an inductor LPF2, a capacitor C3, a capacitor C4, and an inductor L2. The complex voltage and current V_{27} , I_{27} , and ϕ_{27} includes the voltage magnitude V_{27} , the current magnitude I_{27} , and the phase ϕ_{27} between the voltage and current. The complex voltage and current received at the node 261 is the same as the complex voltage and current measured at the node N5 (Figure 1). When both the 2 MHz and 27 MHz RF generators are on and the 60 MHz RF generator is off, the complex voltages and currents V_2 , I_2 , ϕ_2 , V_{27} , I_{27} , and ϕ_{27} are an example of the second complex voltage and current. Moreover, similarly, when the 60 MHz RF generator is on and the 2 and 27 MHz RF generators are off, a complex voltage and current V_{60} , I_{60} , and ϕ_{60} at the output 259 is determined based on a complex voltage and current received at a node 265 and characteristics of an inductor LPF1, a capacitor C1, a capacitor C2, an inductor L4, a capacitor 269, and an inductor L1. The complex voltage and current V_{60} , I_{60} , and ϕ_{60} includes the voltage magnitude V_{60} , the current magnitude I_{60} , and the phase ϕ_{60} between the voltage and current. When the 2 MHz, 27 MHz, and the 60 MHz RF generators are on, the complex voltages and currents V_2 , I_2 , ϕ_2 , V_{27} , I_{27} , ϕ_{27} , V_{60} , I_{60} , and ϕ_{60} are an example of the second complex voltage and current.

[0082] In an operation 117, the RF transmission model 161 (Figure 1) is generated based on the electrical components of the RF transmission line 113 (Figure 1). For example, connections between electrical components of the RF transmission line 113 and characteristics of the electrical components are provided to the processor of the host system 130 by the user via an input device that is coupled with the host system 130. Upon receiving the connections and the characteristics, the processor generates elements that have the same characteristics as that of electrical components of the RF transmission line 113 and generates connections between the elements that are the same as that between the electrical components.

[0083] In an operation 119, the second complex voltage and current is propagated through one or more elements of the RF transmission model portion 173 from the input of the RF transmission model 113 to the output, e.g., the model node N1m (Figure 1), of the RF transmission model portion 173 to determine the third complex voltage and current at the output of the RF transmission model portion 173. For example, with reference to Figure 5B,

when the 2 MHz RF generator is on and the 27 and 60 MHz RF generators are off, a complex voltage and current V_{x4} , I_{x4} , and ϕ_{x4} , e.g., an intermediate complex voltage and current, at a node 293, e.g., an intermediate node, is determined based on an inductance of an inductor L_{tunnel} , based on a capacitance of a capacitor C_{tunnel} , and based on the complex voltage and current V_2 , I_2 , and ϕ_2 (Figure 3B), which is an example of the second complex voltage and current. It should be noted that L_{tunnel} is an inductance of a computer-generated model of an RF tunnel and C_{tunnel} is a capacitance of the RF tunnel model. Moreover, a complex voltage and current V_{21} , I_{21} , and ϕ_{21} at an output 297 of a tunnel and strap model 210 is determined based on the complex voltage and current V_{x4} , I_{x4} , and ϕ_{x4} , and based on an inductance of an inductor L_{strap} . The output 297 is an example of the output, e.g., the model node N_{1m} (Figure 1), of the portion 173 (Figure 1). It should be noted that L_{strap} is an inductance of a computer-generated model of the RF strap. When the 2 MHz RF generator is on and the 27 and 60 MHz RF generators are off, the complex voltage and current V_{21} , I_{21} , and ϕ_{21} is determined to be the third complex voltage and current at the output 297.

[0084] Similarly, when the 27 MHz RF generator is on and the 2 and 60 MHz RF generators are off, a complex voltage and current V_{271} , I_{271} , and ϕ_{271} at the output 297 is determined based on the complex voltage and current V_{27} , I_{27} , ϕ_{27} (Figure 3B) at the output 259 and characteristics of the inductor L_{tunnel} , the capacitor C_{tunnel} , and the inductor L_{strap} . When both the 2 MHz and 27 MHz RF generators are on and the 60 MHz RF generator is off, the complex voltages and currents V_{21} , I_{21} , ϕ_{21} , V_{271} , I_{271} , and ϕ_{271} are an example of the third complex voltage and current.

[0085] Moreover, similarly, when the 60 MHz RF generator is powered on and the 2 and 27 MHz RF generators are powered off, a complex voltage and current V_{601} , I_{601} , and ϕ_{601} at the output 297 is determined based on the complex voltage and current V_{60} , I_{60} , and ϕ_{60} (Figure 3B) received at a node 259 and characteristics of the inductor L_{tunnel} , the capacitor C_{tunnel} , and the inductor L_{strap} . When the 2 MHz, 27 MHz, and the 60 MHz RF generators are on, the complex voltages and currents V_{21} , I_{21} , ϕ_{21} , V_{271} , I_{271} , ϕ_{271} , V_{601} , I_{601} , and ϕ_{601} are an example of the third complex voltage and current. The method 102 ends after the operation 119.

[0086] Figure 3A is a block diagram of an embodiment of a system 123 used to illustrate an impedance matching circuit 122. The impedance matching circuit 122 is an example of the impedance matching circuit 114 (Figure 1). The impedance matching circuit

122 includes series connections between electrical components and/or parallel connections between electrical components.

[0087] Figure 3B is a circuit diagram of an embodiment of an impedance matching model 172. The impedance matching model 172 is an example of the impedance matching model 104 (Figure 1). As shown, the impedance matching model 172 includes capacitors having capacitances C1 thru C9, inductors having inductances LPF1, LPF2, and L1 thru L4. It should be noted that the manner in which the inductors and/or capacitors are coupled with each other in Figure 3B is an example. For example, the inductors and/or capacitors shown in Figure 3B can be coupled in a series and/or parallel manner with each other. Also, in some embodiments, the impedance matching model 172 includes a different number of capacitors and/or a different number of inductors than that shown in Figure 3B.

[0088] Figure 4 is a diagram of an embodiment of a system 178 used to illustrate an RF transmission line 181, which is an example of the RF transmission line 113 (Figure 1). The RF transmission line 181 includes a cylinder 148, e.g., a tunnel. Within a hollow of the cylinder 148 lies an insulator 189 and an RF rod 142. A combination of the cylinder 148 and the RF rod 142 is an example of the portion 169 (Figure 1) of the RF transmission line 113 (Figure 1). The RF transmission line 181 is bolted via bolts B1, B2, B3, and B4 with the impedance matching circuit 114. In one embodiment, the RF transmission line 181 is bolted via any number of bolts with the impedance matching circuit 114. In some embodiments, instead of or in addition to bolts, any other form of attachment, e.g., glue, screws, etc., is used to attach the RF transmission line 181 to the impedance matching circuit 114.

[0089] The RF transmission rod 142 is coupled with the output of the impedance matching circuit 114. Also, an RF strap 144, also known as RF spoon, is coupled with the RF rod 142 and with an RF rod 199, a portion of which is located within a support 146, e.g., a cylinder. The support 146 that includes the RF rod 199 is an example of the portion 195 (Figure 1). In an embodiment, a combination of the cylinder 148, the RF rod 142, the RF strap 144, the support 146 and the RF rod 199 forms the RF transmission line 181, which is an example of the RF transmission line 113 (Figure 1). The support 146 provides support to the plasma chamber. The support 146 is attached to the ESC 177 of the plasma chamber. An RF signal is supplied from the x MHz generator via the cable 150, the impedance matching circuit 114, the RF rod 142, the RF strap 144, and the RF rod 199 to the ESC 177.

[0090] In one embodiment, the ESC 177 includes a heating element and an electrode on top of the heating element. In an embodiment, the ESC 177 includes a heating element and the lower electrode. In one embodiment, the ESC 177 includes the lower electrode and a heating element, e.g., coil wire, etc., embedded within holes formed within the lower electrode. In some embodiments, the electrode is made of a metal, e.g., aluminum, copper, etc. It should be noted that the RF transmission line 181 supplies an RF signal to the lower electrode of the ESC 177.

[0091] Figure 5A is a block diagram of an embodiment of a system 171 used to illustrate a circuit model 176 of the RF transmission line 113 (Figure 1). For example, the circuit model 176 includes inductors and/or capacitors, connections between the inductors, connections between the capacitors, and/or connections between the inductors and the capacitors. Examples of connections include series and/or parallel connections. The circuit model 176 is an example of the RF transmission model 161 (Figure 1).

[0092] Figure 5B is a diagram of an embodiment of an electrical circuit 180 used to illustrate the tunnel and strap model 210, which is an example of the portion 173 (Figure 1) of the RF transmission model 161 (Figure 1). The electrical circuit 180 includes the impedance matching model 172 and the tunnel and strap model 210. The tunnel and strap model 210 includes inductors L_{tunnel} and L_{strap} and a capacitor C_{tunnel} . It should be noted that the inductor L_{tunnel} represents an inductance of the cylinder 148 (Figure 4) and the RF rod 142 and the capacitor C_{tunnel} represents a capacitance of the cylinder 148 and the RF rod 142. Moreover, the inductor L_{strap} represents an inductance of the RF strap 144 (Figure 4).

[0093] In an embodiment, the tunnel and strap model 210 includes any number of inductors and/or any number of capacitors. In this embodiment, the tunnel and strap model 210 includes any manner, e.g., serial, parallel, etc. of coupling a capacitor to another capacitor, coupling a capacitor to an inductor, and/or coupling an inductor to another inductor.

[0094] Figure 5C is a diagram of an embodiment of an electrical circuit 300 used to illustrate a tunnel and strap model 302, which is an example of the portion 173 (Figure 1) of the RF transmission model 161 (Figure 1). The tunnel and strap model 302 is coupled via the output 259 to the impedance matching model 172. The tunnel and strap model 302 includes inductors having inductances 20 nanoHenry (nH) and capacitors having capacitances of 15 picoFarads (pF), 31 pF, 15.5pF, and 18.5 pF. The tunnel and strap model 302 is

coupled via a node 304 to an RF cylinder, which is coupled to the ESC 177 (Figure 1). The RF cylinder is an example of the portion 195 (Figure 1).

[0095] It should be noted that in some embodiments, the inductors and capacitors of the tunnel and strap model 302 have other values. For example, the 20 nH inductors have an inductance ranging between 15 and 20 nH or between 20 and 25 nH. As another example, two or more of the inductors of the tunnel and strap model 302 have different inductances. As yet another example, the 15 pF capacitor has a capacitance ranging between 8 pF and 25 pF, the 31 pF capacitor has a capacitance ranging between 15 pF and 45 pF, the 15.5 pF capacitor has a capacitance ranging between 9 pF and 20 pF, and the 18.5 pF capacitor has a capacitance ranging between 10 pF and 27 pF.

[0096] In various embodiments, any number of inductors are included in the tunnel and strap model 302 and any number of capacitors are included in the tunnel and strap model 302.

[0097] Figure 6 is a diagram of an embodiment of an electrical circuit 310 used to illustrate a cylinder and ESC model 312, which is a combination of an inductor 313 and a capacitor 316. The cylinder and ESC model 312 includes a cylinder model and an ESC model, which is an example of the ESC model 125 (Figure 1). The cylinder model is an example of the portion 197 (Figure 1) of the RF transmission model 161 (Figure 1). The cylinder and ESC model 312 has similar characteristics as that of a combination of the portion 195 and the ESC 177 (Figure 1). For example, the cylinder and ESC model 312 has the same resistance as that of a combination of the portion 195 and the ESC 177. As another example, the cylinder and ESC model 312 has the same inductance as that of a combination of the portion 195 and the ESC 177. As yet another example, the cylinder and ESC model 312 has the same capacitance as that of a combination of the portion 195 and the ESC 177. As yet another example, the cylinder and ESC model 312 has the same inductance, resistance, capacitance, or a combination thereof, as that of a combination of the portion 195 and the ESC 177.

[0098] The cylinder and ESC model 312 is coupled via a node 318 to the tunnel and strap model 302. The node 318 is an example of the model node N1m (Figure 1).

[0099] It should be noted that in some embodiments, an inductor having an inductance other than the 44 milliHenry (mH) is used in the cylinder and ESC model 312. For example, an inductor having an inductance ranging from 35 mH to 43.9 mH or from 45.1

mH too 55 mH is used. In various embodiments, a capacitor having a capacitance other than 550 pF is used. For example, instead of the 550 pF capacitor, a capacitor having a capacitance ranging between 250 and 550 pF or between 550 and 600 pF is used.

[00100] The processor of the host system 130 (Figure 1) calculates a combined impedance, e.g., total impedance, etc., of a combination of the model 172, the tunnel and strap model 302, and the cylinder and ESC model 312. The combined impedance and complex voltage and current determined at the model node 318 are used as inputs by the processor of the host system 130 to calculate a complex voltage and impedance at the node N6m. It should be noted that an output of the cylinder and ESC model 312 is the model node N6m.

[00101] Figure 7 is a block diagram of an embodiment of a system 200 that is used to determine a variable. The system 200 includes a plasma chamber 135, which further includes an ESC 201 and has an input 285. The plasma chamber 135 is an example of the plasma chamber 175 (Figure 1) and the ESC 201 is an example of the ESC 177 (Figure 1). The ESC 201 includes a heating element 198. Also, the ESC 201 is surrounded by an edge ring (ER) 194. The ER 194 includes a heating element 196. In an embodiment, the ER 194 facilitates a uniform etch rate and reduced etch rate drift near an edge of the work piece 131 that is supported by the ESC 201.

[00102] A power supply 206 provides power to the heating element 196 via a filter 208 to heat the heating element 196 and a power supply 204 provides power to the heating element 198 via a filter 202 to heat the heating element 198. In an embodiment, a single power supply provides power to both the heating elements 196 and 198. The filter 208 filters out predetermined frequencies of a power signal that is received from the power supply 206 and the filter 202 filters out predetermined frequencies of a power signal that is received from the power supply 204.

[00103] The heating element 198 is heated by the power signal received from the power supply 204 to maintain an electrode of the ESC 198 at a desirable temperature to further maintain an environment within the plasma chamber 135 at a desirable temperature. Moreover, the heating element 196 is heated by the power signal received from the power supply 206 to maintain the ER 194 at a desirable temperature to further maintain an environment within the plasma chamber 135 at a desirable temperature.

[00104] It should be noted that in an embodiment, the ER 194 and the ESC 201 include any number of heating elements and any type of heating elements. For example, the ESC 201 includes an inductive heating element or a metal plate. In one embodiment, each of the ESC 201 and the ER 194 includes one or more cooling elements, e.g., one or more tubes that allow passage of cold water, etc., to maintain the plasma chamber 135 at a desirable temperature.

[00105] It should further be noted that in one embodiment, the system 200 includes any number of filters. For example, the power supplies 204 and 206 are coupled to the ESC 201 and the ER 194 via a single filter.

[00106] Figure 8A is a diagram of an embodiment of a system 217 used to illustrate a model of the filters 202 and 208 (Figure 7) to improve an accuracy of the variable. The system 217 includes the tunnel and strap model 210 that is coupled via a cylinder model 211 to a model 216, which includes capacitors and/or inductors and connections therebetween of the filters 202 and 208. The model 216 is stored within the storage HU 162 (Figure 1) and/or the other storage HU. The capacitors and/or inductors of the model 216 are coupled with each other in a manner, e.g., a parallel manner, a serial manner, a combination thereof, etc. The model 216 represents capacitances and/or inductances of the filters 202 and 208.

[00107] Moreover, the system 217 includes the cylinder model 211, which is a computer-generated model of the RF rod 199 (Figure 4) and the support 146 (Figure 4). The cylinder model 211 has similar characteristics as that of electrical components of the RF rod 199 and the support 146. The cylinder model 211 includes one or more capacitors, one or more inductors, connections between the inductors, connections between the capacitors, and/or connections between a combination of the capacitors and inductors.

[00108] The processor of the host system 130 (Figure 1) calculates a combined impedance, e.g., total impedance, etc., of the model 216, the tunnel and strap model 210, and the cylinder model 211. The combined impedance provides a complex voltage and impedance at the node N2m. With the inclusion of the model 216 and the tunnel and strap model 214 in determining the variable at the node N2m, accuracy of the variable is improved. It should be noted that an output of the model 216 is the model node N2m.

[00109] Figure 8B is a diagram of an embodiment of a system 219 used to illustrate a model of the filters 202 and 208 (Figure 7) to improve an accuracy of the variable. The

system 219 includes the tunnel and strap model 210 and a model 218, which is coupled in parallel to the tunnel and strap model 210. The model 218 is an example of the model 216 (Figure 8A). The model 218 includes an inductor Lfilter, which represents a combined inductance of the filters 202 and 208. The model 218 further includes a capacitor Cfilter, which represents directed combined capacitance of the filters 202 and 208.

[00110] Figure 9 is a block diagram of an embodiment of a system 236 for using a voltage and current probe 238 to measure a variable at an output 231 of an RF generator 220. The output 231 is an example of the node N3 (Figure 1) or of the node N5 (Figure 1). The RF generator 220 is an example of the x MHz generator or the y MHz generator (Figure 1). The host system 130 generates and provides a digital pulsing signal 213 having two or more states to a digital signal processor (DSP) 226. In one embodiment, the digital pulsing signal 213 is a transistor-transistor logic (TTL) signal. Examples of the states include an on state and an off state, a state having a digital value of 1 and a state having a digital value of 0, a high state and a low state, etc.

[00111] In another embodiment, instead of the host system 130, a clock oscillator, e.g., a crystal oscillator, etc., is used to generate an analog clock signal, which is converted by an analog-to-digital converter into a digital signal similar to the digital pulsing signal 213.

[00112] The digital pulsing signal 213 is sent to the DSP 226. The DSP 226 receives the digital pulsing signal 213 and identifies the states of the digital pulsing signal 213. For example, the DSP 226 determines that the digital pulsing signal 213 has a first magnitude, e.g., the value of 1, the high state magnitude, etc., during a first set of time periods and has a second magnitude, e.g., the value of 0, the low state magnitude, etc., during a second set of time periods. The DSP 226 determines that the digital pulsing signal 213 has a state S1 during the first set of time periods and has a state S0 during the second set of time periods. Examples of the state S0 include the low state, the state having the value of 0, and the off state. Examples of the state S1 include the high state, the state having the value of 1, and the on state. As yet another example, the DSP 226 compares a magnitude of the digital pulsing signal 213 with a pre-stored value to determine that the magnitude of the digital pulsing signal 213 is greater than the pre-stored value during the first set of time periods and that the magnitude during the state S0 of the digital pulsing signal 213 is not greater than the pre-stored value during the second set of time periods. In the embodiment in which the clock oscillator is used, the DSP 226 receives an analog clock signal from the clock oscillator, converts the analog signal into a digital form, and then identifies the two states S0 and S1.

[00113] When a state is identified as S1, the DSP 226 provides a power value P1 and/or a frequency value F1 to a parameter control 222. Moreover, when the state is identified as S0, the DSP 226 provides a power value P0 and/or a frequency value F0 to a parameter control 224. An example of a parameter control that is used to tune a frequency includes an auto frequency tuner (AFT).

[00114] It should be noted that the parameter control 222, the parameter control 224, and the DSP 226 are portions of a control system 187. For example, the parameter control 222 and the parameter control 224 are logic blocks, e.g., tuning loops, etc., which are portions of a computer program that is executed by the DSP 226. In some embodiments, the computer program is embodied within a non-transitory computer-readable medium, e.g., a storage HU.

[00115] In an embodiment, a controller, e.g., hardware controller, ASIC, PLD, etc., is used instead of a parameter control. For example, a hardware controller is used instead of the parameter control 222 and another hardware controller is used instead of the parameter control 224.

[00116] Upon receiving the power value P1 and/or the frequency value F1, the parameter control 222 provides the power value P1 and/or the frequency value F1 to a driver 228 of a drive and amplifier system (DAS) 232. Examples of a driver includes a power driver, a current driver, a voltage driver, a transistor, etc. The driver 228 generates an RF signal having the power value P1 and/or the frequency value F1 and provides the RF signal to an amplifier 230 of the DAS 232.

[00117] In one embodiment, the driver 228 generates an RF signal having a drive power value that is a function of the power value P1 and/or having a drive frequency value that is a function of the frequency value F1. For example, the drive power value is within a few watts, e.g. 1 thru 5 watts, etc., of the power value P1 and the drive frequency value is within a few Hz, e.g. 1 thru 5 Hz, etc., of the frequency value F1.

[00118] The amplifier 230 amplifies the RF signal having the power value P1 and/or the frequency value F1 and generates an RF signal 215 that corresponds to the RF signal received from the driver 228. For example, the RF signal 215 has a higher amount of power than that of the power value P1. As another example, the RF signal 215 has the same amount of power as that of the power value P1. The RF signal 215 is transferred via a cable 217 and the impedance matching circuit 114 to the ESC 177 (Figure 1).

[00119] The cable 217 is an example of the cable 150 or the cable 152 (Figure 1). For example, when the RF generator 220 is an example of the x MHz RF generator (Figure 1), the cable 217 is an example of the cable 150 and when the RF generator 220 is an example of the y MHz RF generator (Figure 1), the cable 217 is an example of the cable 152.

[00120] When the power value P1 and/or the frequency value F1 are provided to the DAS 232 by the parameter control 222 and the RF signal 215 is generated, the voltage and current probe 238 measures values of the variable at the output 231 that is coupled to the cable 217. The voltage and current probe 238 is an example of the voltage and current probe 110 or the voltage and current probe 111 (Figure 1). The voltage and current probe 238 sends the values of the variable via a communication device 233 to the host system 130 for the host system 130 to execute the method 102 (Figure 3) and methods 340, 351, and 363 (Figures 13, 15, and 17) described herein. The communication device 233 is an example of the communication device 185 or 189 (Figure 1). The communication device 233 applies a protocol, e.g., Ethernet, EtherCAT, USB, serial, parallel, packetization, depacketization, etc., to transfer data from the voltage and current probe 238 to the host system 130. In various embodiments, the host system 130 includes a communication device that applies the protocol applied by the communication device 233. For example, when the communication 233 applies packetization, the communication device of the host system 130 applies depacketization. As another example, when the communication device 233 applies a serial transfer protocol, the communication device of the host system 130 applies a serial transfer protocol.

[00121] Similarly, upon receiving the power value P0 and/or the frequency value F0, the parameter control 224 provides the power value P0 and/or the frequency value F0 to the driver 228. The driver 228 creates an RF signal having the power value P0 and/or the frequency value F0 and provides the RF signal to the amplifier 230.

[00122] In one embodiment, the driver 228 generates an RF signal having a drive power value that is a function of the power value P0 and/or having a drive frequency value that is a function of the frequency value F0. For example, the drive power value is within a few, e.g. 1 thru 5, watts of the power value P0 and the drive frequency value is within a few, e.g. 1 thru 5, Hz of the frequency value F0.

[00123] The amplifier 230 amplifies the RF signal having the power value P0 and/or the frequency value F0 and generates an RF signal 221 that corresponds to the RF

signal received from the driver 228. For example, the RF signal 221 has a higher amount of power than that of the power value P0. As another example, the RF signal 221 has the same amount of power as that of the power value P0. The RF signal 221 is transferred via the cable 217 and the impedance matching circuit 114 to the known load 112 (Figure 2).

[00124] When the power value P0 and/or the frequency value F0 are provided to the DAS 232 by the parameter control 222 and the RF signal 121 is generated, the voltage and current probe 238 measures values of the variable at the output 231. The voltage and current probe 238 sends the values of the variable to the host system 130 for the host system 130 to execute the method 102 (Figure 2), the method 340 (Figure 13), the method 351 (Figure 15), or the method 363 (Figure 17).

[00125] It should be noted that the in one embodiment, the voltage and current probe 238 is decoupled from the DSP 226. In some embodiments, the voltage and current probe 238 is coupled to the DSP 226. It should further be noted that the RF signal 215 generated during the state S1 and the RF signal 221 generated during the state S0 are portions of a combined RF signal. For example, the RF signal 215 is a portion of the combined RF signal that has a higher amount of power than the RF signal 221, which is another portion of the combined RF signal.

[00126] Figure 10 is a block diagram of an embodiment of a system 250 in which the voltage and current probe 238 and the communication device 233 are located outside the RF generator 220. In Figure 1, the voltage and current probe 110 is located within the x MHz RF generator to measure the variable at the output of the x MHz RF generator. The voltage and current probe 238 is located outside the RF generator 220 to measure the variable at the output 231 of the RF generator 220. The voltage and current probe 238 is associated, e.g., coupled, to the output 231 of the RF generator 220.

[00127] Figure 11 is a block diagram of an embodiment of a system 128 in which the values of the variable determined using the system 126 of Figure 1 are used. The system 128 includes an m MHz RF generator, an n MHz RF generator, an impedance matching circuit 115, an RF transmission line 287, and a plasma chamber 134. The plasma chamber 134 may be similar to the plasma chamber 175.

[00128] It should be noted that in an embodiment, the x MHz RF generator of Figure 2 is similar to the m MHz RF generator and the y MHz RF generator of Figure 2 is similar to the n MHz RF generator. As an example, x MHz is equal to m MHz and y MHz is

equal to n MHz. As another example, the x MHz generator and the m MHz generators have similar frequencies and the y MHz generator and the n MHz generator have similar frequencies. An example of similar frequencies is when the x MHz is within a window, e.g., within kHz or Hz, of the m MHz frequency. In some embodiments, the x MHz RF generator of Figure 2 is not similar to the m MHz RF generator and the y MHz RF generator of Figure 2 is not similar to the n MHz RF generator.

[00129] It is further noted that in various embodiments, a different type of sensor is used in each of the m MHz and n MHz RF generators than that used in each of the x MHz and y MHz RF generators. For example, a sensor that does not comply with the NIST standard is used in the m MHz RF generator. As another example, a voltage sensor that measures only voltage is used in the m MHz RF generator.

[00130] It should further be noted that in an embodiment, the impedance matching circuit 115 is similar to the impedance matching circuit 114 (Figure 1). For example, an impedance of the impedance matching circuit 114 is the same as an impedance of the impedance matching circuit 115. As another example, an impedance of the impedance matching circuit 115 is within a window, e.g., within 10-20%, of the impedance of the impedance matching circuit 114. In some embodiments, the impedance matching circuit 115 is not similar to the impedance matching circuit 114.

[00131] The impedance matching circuit 115 includes electrical components, e.g., inductors, capacitors, etc., to match an impedance of a power source coupled to the impedance matching circuit 115 with an impedance of a load coupled to the circuit 115. For example, the impedance matching circuit 114 matches an impedance of a source coupled to the impedance matching circuit 114, e.g., a combination of the m MHz RF generator, the n MHz RF generator, and cables coupling the m and n MHz RF generators to the impedance matching circuit 114, etc., with an impedance of a load, e.g., a combination of the plasma chamber 134 and the RF transmission line 287, etc.

[00132] It should be noted that in an embodiment, the RF transmission line 287 is similar to the RF transmission line 113 (Figure 1). For example, an impedance of the RF transmission line 287 is the same as an impedance of the RF transmission line 113. As another example, an impedance of the RF transmission line 287 is within a window, e.g., within 10-20%, of the impedance of the RF transmission line 113. In various embodiments, the RF transmission line 287 is not similar to the RF transmission line 113.

[00133] The plasma chamber 134 includes an ESC 192, an upper electrode 264, and other parts (not shown), e.g., an upper dielectric ring surrounding the upper electrode 264, an upper electrode extension surrounding the upper dielectric ring, a lower dielectric ring surrounding a lower electrode of the ESC 192, a lower electrode extension surrounding the lower dielectric ring, an upper plasma exclusion zone (PEZ) ring, a lower PEZ ring, etc. The upper electrode 264 is located opposite to and facing the ESC 192. A work piece 262, e.g., a semiconductor wafer, etc., is supported on an upper surface 263 of the ESC 192. Each of the upper electrode 264 and the lower electrode of the ESC 192 is made of a metal, e.g., aluminum, alloy of aluminum, copper, etc.

[00134] In one embodiment, the upper electrode 264 includes a hole that is coupled to a central gas feed (not shown). The central gas feed receives one or more process gases from a gas supply (not shown). The upper electrode 264 is grounded. The ESC 192 is coupled to the m MHz RF generator and the n MHz RF generator via the impedance matching circuit 115.

[00135] When the process gas is supplied between the upper electrode 264 and the ESC 192 and when the m MHz RF generator and/or the n MHz RF generator supplies power via the impedance matching circuit 115 to the ESC 192, the process gas is ignited to generate plasma within the plasma chamber 134.

[00136] It should be noted that the system 128 lacks a probe, e.g., a metrology tool, a voltage and current probe, a voltage probe, etc., to measure the variable at an output 283 of the impedance matching circuit 115, at a point on the RF transmission line 287, or at the ESC 192. The values of the variable at the model nodes N1m, N2m, N4m, and N6m are used to determine whether the system 128 is functioning as desired.

[00137] In various embodiments, the system 128 lacks a wafer bias sensor, e.g., an in-situ direct current (DC) probe pick-up pin, and related hardware that is used to measure wafer bias at the ESC 192. The nonuse of the wafer bias sensor and the related hardware saves cost.

[00138] It should also be noted that in an embodiment, the system 128 includes any number of RF generators coupled to an impedance matching circuit.

[00139] Figures 12A, 12B, and 12C are diagrams of embodiments of graphs 268, 272, and 275 that illustrate a correlation between voltage, e.g., root mean square (RMS) voltage, peak voltage, etc., that is measured at the output, e.g., the node N4, of the impedance

matching circuit 114 (Figure 1) within the system 126 (Figure 1) by using a voltage probe and a voltage, e.g., peak voltage, etc., at a corresponding model node output, e.g., the node N4m, determined using the method 102 (Figure 2). Moreover, Figures 12A, 12C, and 12E are diagrams of embodiments of graphs 270, 274, and 277 that illustrate a correlation between current, e.g., root mean square (RMS) current, etc., that is measured the output, e.g., the node N4, of the system 126 (Figure 1) by using a current probe and a current, e.g., RMS current, etc., at a corresponding output, e.g., the node N4m, determined using the method 102 (Figure 2).

[00140] The voltage determined using the method 102 is plotted on an x-axis in each graph 268, 272, and 275 and the voltage measured with the voltage probe is plotted on a y-axis in each graph 268, 272, and 275. Similarly, the current determined using the method 102 is plotted on an x-axis in each graph 270, 274, and 277 and the current measured with the current probe is plotted on a y-axis in each graph 270, 274, and 277.

[00141] The voltages are plotted in the graph 268 when the x MHz RF generator is on and the y MHz RF generator and a z MHz RF generator, e.g., 60 MHz RF generator, are off. Moreover, the voltages are plotted in the graph 272 when the y MHz RF generator is on and the x and z MHz RF generators are off. Also, the voltages are plotted in the graph 275 when the z MHz RF generator is on and the x and y MHz RF generators are off.

[00142] Similarly, currents are plotted in the graph 270 when the x MHz RF generator is on and the y MHz RF generator and a z MHz RF generator are off. Also, the currents are plotted in the graph 274 when the y MHz RF generator is on and the x and z MHz RF generators are off. Also, the currents are plotted in the graph 277 when the z MHz RF generator is on and the x and y MHz RF generators are off.

[00143] It can be seen in each graph 268, 272, and 275 that an approximately linear correlation exists between the voltage plotted on the y-axis of the graph and the voltage plotted on the x-axis of the graph. Similarly, it can be seen in each graph 270, 274, and 277 that an approximately linear correlation exists between the current plotted on the y-axis and the current plotted on the x-axis.

[00144] Figure 13 is a flowchart of an embodiment of the method 340 for determining wafer bias at a model node, e.g., the model node N4m, the model node N1m, the model node N2m, the model node N6m, etc., of the plasma system 126 (Figure 1). It should be noted that in some embodiments, wafer bias is a direct current (DC) voltage that is created

by plasma generated within the plasma chamber 175 (Figure 1). In these embodiments, the wafer bias is present on a surface, e.g., the upper surface 183, of the ESC 177 (Figure 1) and/or on a surface, e.g., an upper surface, of the work piece 131 (Figure 1).

[00145] It should further be noted that the model nodes N1m and N2m are on the RF transmission model 161 (Figure 1) and the model node N6m is on the ESC model 125 (Figure 1). The method 340 is executed by the processor of the host system 130 (Figure 1). In the method 340, the operation 106 is performed.

[00146] Moreover, in an operation 341, one or more models, e.g. the impedance matching model 104, the RF transmission model 161, the ESC model 125 (Figure 1), a combination thereof, etc., of corresponding one or more devices, e.g., the impedance matching circuit 114, the RF transmission line 113, the ESC 177, a combination thereof, etc., are generated. For example, the ESC model 125 is generated with similar characteristics to that of the ESC 177 (Figure 1).

[00147] In an operation 343, the complex voltage and current identified in the operation 106 is propagated through one or more elements of the one or more models to determine a complex voltage and current at an output of the one or more models. For example, the second complex voltage and current is determined from the first complex voltage and current. As another example, the second complex voltage and current is determined from the first complex voltage and current and the third complex voltage and current is determined from the second complex voltage and current. As yet another example, the second complex voltage and current is determined from the first complex voltage and current, the third complex voltage and current is determined from the second complex voltage and current, and the third complex voltage and current is propagated through the portion 197 of the RF transmission model 161 (Figure 1) to determine a fourth complex voltage and current at the model node N2m. In this example, the fourth complex voltage and current is determined by propagating the third complex voltage and current through impedances of elements of the portion 197. As yet another example, the RF transmission model 161 provides an algebraic transfer function that is executed by the processor of the host system 130 to translate the complex voltage and current measured at one or more outputs of one or more RF generators to an electrical node, e.g., the model node N1m, the model node N2m, etc., along the RF transmission model 161.

[00148] As another example of the operation 343, the second complex voltage and current is determined from the first complex voltage and current, the third complex voltage and current is determined from the second complex voltage and current, the fourth complex voltage and current is determined from the third complex voltage and current, and the fourth complex voltage and current is propagated through the ESC model 125 to determine a fifth complex voltage and current at the model node N6m. In this example, the fifth complex voltage and current is determined by propagating the fourth complex voltage and current through impedances of elements, e.g., capacitors, inductors, etc., of the ESC model 125.

[00149] In an operation 342, a wafer bias is determined at the output of the one or more models based on a voltage magnitude of the complex voltage and current at the output, a current magnitude of the complex voltage and current at the output, and a power magnitude of the complex voltage and current at the output. For example, wafer bias is determined based on a voltage magnitude of the second complex voltage and current, a current magnitude of the second complex voltage and current, and a power magnitude of the second complex voltage and current. To further illustrate, when the x MHz RF generator is on and the y MHz and z MHz RF generators are off, the processor of the host system 130 (Figure 1) determines wafer bias at the model node N4m (Figure 1) as a sum of a first product, a second product, a third product, and a constant. In this illustration, the first product is a product of a first coefficient and the voltage magnitude of the second complex voltage and current, the second product is a product of a second coefficient and the current magnitude of the second complex voltage and current, and the third product is a product of a square root of a third coefficient and a square root of a power magnitude of the second complex voltage and current.

[00150] As an example, a power magnitude is a power magnitude of delivered power, which is determined by the processor of the host system 130 as a difference between forward power and reflected power. Forward power is power supplied by one or more RF generators of the system 126 (Figure 1) to the plasma chamber 175 (Figure 1). Reflected power is power reflected back from the plasma chamber 175 towards one or more RF generators of the system 126 (Figure 1). As an example, a power magnitude of a complex voltage and current is determined by the processor of the host system 130 as a product of a current magnitude of the complex voltage and current and a voltage magnitude of the complex voltage and current. Moreover, each of a coefficient and a constant used to determine a wafer bias is a positive or a negative number. As another example of

determination of the wafer bias, when the x MHz RF generator is on and the y and z MHz RF generators are off, the wafer bias at a model node is represented as $ax \cdot V_x + bx \cdot I_x + cx \cdot \sqrt{P_x} + dx$, where "ax" is the first coefficient, "bx" is the second coefficient, "dx" is the constant, "Vx" is a voltage magnitude of a complex voltage and current at the model node, "Ix" is a current magnitude of the complex voltage and current at the model node, and "Px" is a power magnitude of the complex voltage and current at the model node. It should be noted that "sqrt" is a square root operation, which is performed by the processor of the host system 130. In some embodiments, the power magnitude Px is a product of the current magnitude Ix and the voltage magnitude Vx.

[00151] In various embodiments, a coefficient used to determine a wafer bias is determined by the processor of the host system 130 (Figure 1) based on a projection method. In the projection method, a wafer bias sensor, e.g., a wafer bias pin, etc., measures wafer bias on a surface, e.g., the upper surface 183 (Figure 1), etc., of the ESC 177 for a first time. Moreover, in the projection method, a voltage magnitude, a current magnitude, and a power magnitude are determined at a model node within the plasma system 126 based on complex voltage and current measured at an output of an RF generator. For example, the complex voltage and current measured at the node N3 (Figure 1) for the first time is propagated by the processor of the host system 130 to a model node, e.g., the model node N4m, the model node N1m, the model node N2m, or the model node N6m (Figure 1), etc., to determine complex voltage and current at the model node for the first time. Voltage magnitude and current magnitude are extracted by the processor of the host system 130 from the complex voltage and current at the model node for the first time. Also, power magnitude is calculated by the processor of the host system 130 as a product of the current magnitude and the voltage magnitude for the first time.

[00152] Similarly, in the example, complex voltage and current is measured at the node N3 for one or more additional times and the measured complex voltage and current is propagated to determine complex voltage and current at the model node, e.g., the model node N4m, the model node N1m, the model node N2m, the model node N6m, etc., for the one or more additional times. Also, for the one or more additional times, voltage magnitude, current magnitude, and power magnitude are extracted from the complex voltage and current determined for the one or more additional times. A mathematical function, e.g., partial least squares, linear regression, etc., is applied by the processor of the host system 130 to the voltage magnitude, the current magnitude, the power magnitude, and the measured wafer bias

obtained for the first time and for the one or more additional times to determine the coefficients a_x , b_x , c_x and the constant d_x .

[00153] As another example of the operation 342, when the y MHz RF generator is on and the x and z MHz RF generators are off, a wafer bias is determined as $a_y \cdot V_y + b_y \cdot I_y + c_y \cdot \sqrt{P_y} + d_y$, where " a_y " is a coefficient, " b_y " is a coefficient, " d_y " is a constant, " V_y " is a voltage magnitude of the second complex voltage and current, " I_y " is a current magnitude of the second complex voltage and current, and " P_y " is a power magnitude of the second complex voltage and current. The power magnitude P_y is a product of the current magnitude I_y and the voltage magnitude V_y . As yet another example of the operation 342, when the z MHz RF generator is on and the x and y MHz RF generators are off, a wafer bias is determined as $a_z \cdot V_z + b_z \cdot I_z + c_z \cdot \sqrt{P_z} + d_z$, where " a_z " is a coefficient, " b_z " is a coefficient, " d_z " is a constant, " V_z " is a voltage magnitude of the second complex voltage and current, " I_z " is a current magnitude of the second complex voltage and current, and " P_z " is a power magnitude of the second complex voltage and current. The power magnitude P_z is a product of the current magnitude I_z and the voltage magnitude V_z .

[00154] As another example of the operation 342, when the x and y MHz RF generators are on and the z MHz RF generator is off, the wafer bias is determined as a sum of a first product, a second product, a third product, a fourth product, a fifth product, a sixth product, and a constant. The first product is a product of a first coefficient and the voltage magnitude V_x , the second product is a product of a second coefficient and the current magnitude I_x , the third product is a product of a third coefficient and a square root of the power magnitude P_x , the fourth product is a product of a fourth coefficient and the voltage magnitude V_y , the fifth product is a product of a fifth coefficient and the current magnitude I_y , and the sixth product is a product of a sixth coefficient and a square root of the power magnitude P_y . When the x and y MHz RF generators are on and the z MHz RF generator is off, the wafer bias is represented as $a_{xy} \cdot V_x + b_{xy} \cdot I_x + c_{xy} \cdot \sqrt{P_x} + d_{xy} \cdot V_y + e_{xy} \cdot I_y + f_{xy} \cdot \sqrt{P_y} + g_{xy}$, where " a_{xy} ", " b_{xy} ", " c_{xy} ", " d_{xy} ", " e_{xy} ", " f_{xy} ", " d_{xy} ", " e_{xy} ", and " f_{xy} " are coefficients, and " g_{xy} " is a constant.

[00155] As another example of the operation 342, when the y and z MHz RF generators are on and the x MHz RF generator is off, a wafer bias is determined as $a_{yz} \cdot V_y + b_{yz} \cdot I_y + c_{yz} \cdot \sqrt{P_y} + d_{yz} \cdot V_z + e_{yz} \cdot I_z + f_{yz} \cdot \sqrt{P_z} + g_{yz}$, where " a_{yz} ", " b_{yz} ", " c_{yz} ", " d_{yz} ", " e_{yz} ", and " f_{yz} " are coefficients, and " g_{yz} " is a constant. As yet another example of the operation 342, when the x and z MHz RF generators are on and the y MHz RF generator

is off, a wafer bias is determined as $axz \cdot V_x + bxz \cdot I_x + cxz \cdot \sqrt{P_x} + dxz \cdot V_z + exz \cdot I_z + fxz \cdot \sqrt{P_z} + gxz$, where "axz", "bxz", "cxz", "dxz", "exz", and "fxz" are coefficients, and gxz is a constant.

[00156] As another example of the operation 342, when the x, y, and z MHz RF generators are on, the wafer bias is determined as a sum of a first product, a second product, a third product, a fourth product, a fifth product, a sixth product, a seventh product, an eighth product, a ninth product, and a constant. The first product is a product of a first coefficient and the voltage magnitude V_x , the second product is a product of a second coefficient and the current magnitude I_x , the third product is a product of a third coefficient and a square root of the power magnitude P_x , the fourth product is a product of a fourth coefficient and the voltage magnitude V_y , the fifth product is a product of a fifth coefficient and the current magnitude I_y , the sixth product is a product of a sixth coefficient and a square root of the power magnitude P_y , the seventh product is a product of a seventh coefficient and the voltage magnitude V_z , the eighth product is a product of an eighth coefficient and the current magnitude I_z , and the ninth product is a product of a ninth coefficient and a square root of a power magnitude P_z . When the x, y, and z MHz RF generators are on, the wafer bias is represented as $axyz \cdot V_x + bxyz \cdot I_x + cxyz \cdot \sqrt{P_x} + dxyz \cdot V_y + exyz \cdot I_y + fxyz \cdot \sqrt{P_y} + gxyz \cdot V_z + hxyz \cdot I_z + ixyz \cdot \sqrt{P_z} + jxyz$, where "axyz", "bxyz", "cxyz", "dxyz", "exyz", "fxyz", "gxyz", "hxyz", and "ixyz" are coefficients, and "jxyz" is a constant.

[00157] As another example of determination of wafer bias at the output of the one or more models, wafer bias at the model node N1m is determined by the processor of the host system 130 based on voltage and current magnitudes determined at the model node N1m. To further illustrate, the second complex voltage and current is propagated along the portion 173 (Figure 1) to determine complex voltage and current at the model node N1m. The complex voltage and current is determined at the model node N1m from the second complex voltage and current in a manner similar to that of determining the second complex voltage and current from the first complex voltage and current. For example, the second complex voltage and current is propagated along the portion 173 based on characteristics of elements of the portion 173 to determine a complex voltage and current at the model node N1m.

[00158] Based on the complex voltage and current determined at the model node N1m, wafer bias is determined at the model node N1m by the processor of the host system 130. For example, wafer bias is determined at the model node N1m from the complex voltage and current at the model node N1m in a manner similar to that of determining the

wafer bias at the model node N4m from the second complex voltage and current. To illustrate, when the x MHz RF generator is on and the y MHz and z MHz RF generators are off, the processor of the host system 130 (Figure 1) determines wafer bias at the model node N1m as a sum of a first product, a second product, a third product, and a constant. In this example, the first product is a product of a first coefficient and the voltage magnitude of the complex voltage and current at the model node N1m, the second product is a product of a second coefficient and the current magnitude of the complex voltage and current at the model node N1m, and the third product is a product of a square root of a third coefficient and a square root of a power magnitude of the complex voltage and current at the model node N1m. When the x MHz RF generator is on and the y and z MHz RF generators are off, the wafer bias at the model node N1m is represented as $ax*Vx + bx*Ix + cx*\sqrt{Px} + dx$, where ax is the first coefficient, bx is the second coefficient, cx is the third coefficient, dx is the constant, Vx is the voltage magnitude at the model node N1m, Ix is the current magnitude at the model node N1m, and Px is the power magnitude at the model node N1m.

[00159] Similarly, based on the complex voltage and current at the model node N1m and based on which of the x, y, and z MHz RF generators are on, the wafer bias $ay*Vy + by*Iy + cy*\sqrt{Py} + dy$, $az*Vz + bz*Iz + cz*\sqrt{Pz} + dz$, $axy*Vx + bxy*Ix + cxy*\sqrt{Px} + dxy*Vy + exy*Iy + fxy*\sqrt{Py} + gxy$, $axz*Vx + bxz*Ix + cxz*\sqrt{Px} + dxz*Vz + exz*Iz + fxz*\sqrt{Pz} + gxz$, $ayz*Vy + byz*Iy + cyz*\sqrt{Py} + dyz*Vz + eyz*Iz + fyz*\sqrt{Pz} + gyz$, and $axyz*Vx + bxyz*Ix + cxyz*\sqrt{Px} + dxyz*Vy + exyz*Iy + fxyz*\sqrt{Py} + gxyz*Vz + hxyz*Iz + ixyz*\sqrt{Pz} + jxyz$ are determined.

[00160] As yet another example of determination of wafer bias at the output of the one or more models, wafer bias at the model node N2m is determined by the processor of the host system 130 based on voltage and current magnitudes determined at the model node N2m in a manner similar to that of determining wafer bias at the model node N1m based on voltage and current magnitudes determined at the model node N1m. To further illustrate, wafer bias $ax*Vx + bx*Ix + cx*\sqrt{Px} + dx$, $ay*Vy + by*Iy + cy*\sqrt{Py} + dy$, $az*Vz + bz*Iz + cz*\sqrt{Pz} + dz$, $axy*Vx + bxy*Ix + cxy*\sqrt{Px} + dxy*Vy + exy*Iy + fxy*\sqrt{Py} + gxy$, $axz*Vx + bxz*Ix + cxz*\sqrt{Px} + dxz*Vz + exz*Iz + fxz*\sqrt{Pz} + gxz$, $ayz*Vy + byz*Iy + cyz*\sqrt{Py} + dyz*Vz + eyz*Iz + fyz*\sqrt{Pz} + gyz$, and $axyz*Vx + bxyz*Ix + cxyz*\sqrt{Px} + dxyz*Vy + exyz*Iy + fxyz*\sqrt{Py} + gxyz*Vz + hxyz*Iz + ixyz*\sqrt{Pz} + jxyz$ are determined at the model node N2m.

[00161] As another example of determination of wafer bias at the output of the one or more models, wafer bias at the model node N6m is determined by the processor of the host system 130 based on voltage and current magnitudes determined at the model node N6m in a manner similar to that of determining wafer bias at the model node N2m based on voltage and current magnitudes determined at the model node N2m. To further illustrate, wafer bias $ax*Vx + bx*Ix + cx*\sqrt{Px} + dx$, $ay*Vy + by*Iy + cy*\sqrt{Py} + dy$, $az*Vz + bz*Iz + cz*\sqrt{Pz} + dz$, $axy*Vx + bxy*Ix + cxy*\sqrt{Px} + dxy*Vy + exy*Iy + fxy*\sqrt{Py} + gxy$, $axz*Vx + bxz*Ix + cxz*\sqrt{Px} + dxz*Vz + exz*Iz + fxz*\sqrt{Pz} + gxz$, $ayz*Vy + byz*Iy + cyz*\sqrt{Py} + dyz*Vz + eyz*Iz + fyz*\sqrt{Pz} + gyz$, and $axyz*Vx + bxyz*Ix + cxyz*\sqrt{Px} + dxyz*Vy + exyz*Iy + fxyz*\sqrt{Py} + gxyz*Vz + hxyz*Iz + ixyz*\sqrt{Pz} + jxyz$ are determined at the model node N6m.

[00162] It should be noted that in some embodiments, wafer bias is stored within the storage HU 162 (Figure 1).

[00163] Figure 14 is a state diagram illustrating an embodiment of a wafer bias generator 340, which is implemented within the host system 130 (Figure 1). When all of the x, y, and z MHz RF generators are off, wafer bias is zero or minimal at a model node, e.g., the model node N4m, N1m, N2m, N6m (Figure 1), etc. When the x, y, or z MHz RF generator is on and the remaining of the x, y, and z MHz RF generators are off, the wafer bias generator 340 determines a wafer bias at a model node, e.g., the model node N4m, N1m, N2m, N6m, etc., as a sum of a first product $a*V$, a second product $b*I$, a third product $c*\sqrt{P}$, and a constant d , where V is a voltage magnitude of a complex voltage and current at the model node, I is a current magnitude of the complex voltage and current, P is a power magnitude of the complex voltage and current, a is a coefficient, b is a coefficient, c is a coefficient, and d is a constant. In various embodiments, a power magnitude at a model node is a product of a current magnitude at the model node and a voltage magnitude at the model node. In some embodiments, the power magnitude is a magnitude of delivered power.

[00164] When two of the x, y, and z MHz RF generators are on and the remaining of the x, y, and z MHz RF generators are off, the wafer bias generator 340 determines a wafer bias at a model node, e.g., the model node N4m, N1m, N2m, N6m, etc., as a sum of a first product $a12*V1$, a second product $b12*I1$, a third product $c12*\sqrt{P1}$, a fourth product $d12*V2$, a fifth product $e12*I2$, a sixth product $f12*\sqrt{P2}$, and a constant $g12$, where " $V1$ " is a voltage magnitude of a complex voltage and current at the model node determined by propagating a voltage measured at an output of a first one of the RF generators that is on, " $I1$ "

is a current magnitude of the complex voltage and current determined by propagating a current measured at the output of the first RF generator that is on, "P1" is a power magnitude of the complex voltage and current determined as a product of V1 and I1, "V2" is a voltage magnitude of the complex voltage and current at the model node determined by propagating a voltage measured at an output of a second one of the RF generators that is on, "I2" is a current magnitude of the complex voltage and current determined by propagating the current measured at an output of the second RF generator that is on, "P2" is a power magnitude determined as a product of V2 and I2, each of "a12", "b12", "c12", "d12", "e12" and "f12" is a coefficient, and "g12" is a constant.

[00165] When all of the x, y, and z MHz RF generators are on, the wafer bias generator 340 determines a wafer bias at a model node, e.g., the model node N4m, N1m, N2m, N6m, etc., as a sum of a first product $a_{123} \cdot V_1$, a second product $b_{123} \cdot I_1$, a third product $c_{123} \cdot \sqrt{P_1}$, a fourth product $d_{123} \cdot V_2$, a fifth product $e_{123} \cdot I_2$, a sixth product $f_{123} \cdot \sqrt{P_2}$, a seventh product $g_{123} \cdot V_3$, an eighth product $h_{123} \cdot I_3$, a ninth product $i_{123} \cdot \sqrt{P_3}$, and a constant j_{123} , where "V1" is a voltage magnitude of a complex voltage and current at the model node determined by propagating a voltage measured at an output of a first one of the RF generators, "I1" is a current magnitude of the complex voltage and current determined by propagating a current measured at the output of the first RF generator, "P1" is a power magnitude of the complex voltage and current determined as a product of V1 and I1, "V2" is a voltage magnitude of the complex voltage and current at the model node determined by propagating a voltage measured at an output of a second one of the RF generators, "I2" is a current magnitude of the complex voltage and current determined by propagating a current measured at the output of the second RF generator, "P2" is a power magnitude of the complex voltage and current determined as a product of V2 and I2, "V3" is a voltage magnitude of the complex voltage and current at the model node determined by propagating a voltage measured at an output of a third one of the RF generators, "I3" is a current magnitude of the complex voltage and current determined by propagating a current at the output of the third RF generator, "P3" is a power magnitude of the complex voltage and current determined as a product of V3 and I3, each of "a123", "b123", "c123", "d123", "e123", "f123", "g123", "h123", and "i123" is a coefficient, and "j123" is a constant.

[00166] Figure 15 is a flowchart of an embodiment of the method 351 for determining a wafer bias at a point along a path 353 (Figure 16) between the model node N4m (Figure 16) and the ESC model 125 (Figure 16). Figure 15 is described with reference

to Figure 16, which is a block diagram of an embodiment of a system 355 for determining a wafer bias at an output of a model.

[00167] In an operation 357, output of the x, y, or z MHz RF generator is detected to identify a generator output complex voltage and current. For example, the voltage and current probe 110 (Figure 1) measures complex voltage and current at the node N3 (Figure 1). In this example, the complex voltage and current is received from the voltage and current probe 110 via the communication device 185 (Figure 1) by the host system 130 (Figure 1) for storage within the storage HU 162 (Figure 1). Also, in the example, the processor of the host system 130 identifies the complex voltage and current from the storage HU 162.

[00168] In an operation 359, the processor of the host system 130 uses the generator output complex voltage and current to determine a projected complex voltage and current at a point along the path 353 between the model node N4m and the model node N6m. The path 161 extends from the model node N4m to the model node N6m. For example, the fifth complex voltage and current is determined from the complex voltage and current measured at the output of the x MHz RF generator, the y MHz RF generator, or the z MHz RF generator. As another example, the complex voltage and current measured at the node N3 or the node N5 is propagated via the impedance matching model 104 to determine a complex voltage and current at the model node N4m (Figure 1). In the example, the complex voltage and current at the model node N4m is propagated via one or more elements of the RF transmission model 161 (Figure 16) and/or via one or more elements of the ESC model 125 (Figure 16) to determine complex voltage and current at a point on the path 353.

[00169] In an operation 361, the processor of the host system 130 applies the projected complex voltage and current determined at the point on the path 353 as an input to a function to map the projected complex voltage and current to a wafer bias value at the node N6m of the ESC model 125 (Figure 15). For example, when the x, y, or z MHz RF generator is on, a wafer bias at the model node N6m is determined as a sum of a first product $a \cdot V$, a second product $b \cdot I$, a third product $c \cdot \sqrt{P}$, and a constant d , where, V is a voltage magnitude of the projected complex voltage and current at the model node N6m, I is a current magnitude of the projected complex voltage and current at the model node N6m, P is a power magnitude of the projected complex voltage and current at the model node N6m, a , b , and c are coefficients, and d is a constant.

[00170] As another example, when two of the x, y, and z MHz RF generators are on and the remaining of the x, y, and z MHz RF generators are off, a wafer bias at the model node N6m is determined as a sum of a first product $a_{12} \cdot V_1$, a second product $b_{12} \cdot I_1$, a third product $c_{12} \cdot \sqrt{P_1}$, a fourth product $d_{12} \cdot V_2$, a fifth product $e_{12} \cdot I_2$, a sixth product $f_{12} \cdot \sqrt{P_2}$, and a constant g_{12} , where V_1 is a voltage magnitude at the model node N6m as a result of a first one of the two RF generators being on, I_1 is a current magnitude at the model node N6m as a result of the first RF generator being on, P_1 is a power magnitude at the model node N6m as a result of the first RF generator being on, V_2 is a voltage magnitude at the model node N6m as a result of a second one of the two RF generators being on, I_2 is a current magnitude at the model node N6m as a result of the second RF generator being on, and P_2 is a power magnitude at the model node N6m as a result of the second RF generator being on, a_{12} , b_{12} , c_{12} , d_{12} , e_{12} , and f_{12} are coefficients, and g_{12} is a constant.

[00171] As yet another example, when all of the x, y, and z MHz RF generators are on, a wafer bias at the model node N6m is determined as a sum of a first product $a_{123} \cdot V_1$, a second product $b_{123} \cdot I_1$, a third product $c_{123} \cdot \sqrt{P_1}$, a fourth product $d_{123} \cdot V_2$, a fifth product $e_{123} \cdot I_2$, a sixth product $f_{123} \cdot \sqrt{P_2}$, a seventh product $g_{123} \cdot V_3$, an eighth product $h_{123} \cdot I_3$, a ninth product $i_{123} \cdot \sqrt{P_3}$, and a constant j_{123} , where V_1 , I_1 , P_1 , V_2 , I_2 , and P_2 are described above in the preceding example, V_3 is a voltage magnitude at the model node N6m as a result of a third one of the RF generators being on, I_3 is a current magnitude at the model node N6m as a result of the third RF generator being on, and P_3 is a power magnitude at the model node N6m as a result of the third RF generator being on, a_{123} , b_{123} , c_{123} , d_{123} , e_{123} , f_{123} , g_{123} , h_{123} , and i_{123} are coefficients and j_{123} is a constant.

[00172] As another example, a function used to determine a wafer bias is a sum of characterized values and a constant. The characterized values include magnitudes, e.g., the magnitudes V , I , P , V_1 , I_1 , P_1 , V_2 , I_2 , P_2 , V_3 , I_3 , P_3 , etc. The characterized values also include coefficients, e.g., the coefficients, a , b , c , a_{12} , b_{12} , c_{12} , d_{12} , e_{12} , f_{12} , a_{123} , b_{123} , c_{123} , d_{123} , e_{123} , f_{123} , g_{123} , h_{123} , i_{123} , etc. Examples of the constant include the constant d , the constant g_{12} , the constant j_{123} , etc.

[00173] It should be noted that the coefficients of the characterized values and the constant of the characterized values incorporate empirical modeling data. For example, wafer bias is measured for multiple times at the ESC 177 (Figure 1) using a wafer bias sensor. Moreover, in the example, for the number of times the wafer bias is measured, complex voltages and currents at the point along the path 353 (Figure 16) are determined by

propagating the complex voltage and current from one or more of the nodes, e.g., the nodes N3, N5, etc., of one or more of the RF generators, e.g., the x MHz RF generator, the y MHz RF generator, the z MHz RF generator, etc., via one or more of the models, e.g., the impedance matching model 104, the model portion 173, the RF transmission model 161, the ESC model 125 (Figure 1), to reach to the point on the path 353 (Figure 16). Moreover, in this example, a statistical method, e.g., partial least squares, regression, etc., is applied by the processor of the host system 130 to the measured wafer bias and to voltage magnitudes, current magnitudes, and power magnitudes extracted from the complex voltages and currents at the point to determine the coefficients of the characterized values and the constant of the characterized values.

[00174] In various embodiments, a function used to determine a wafer bias is characterized by a summation of values that represent physical attributes of the path 353. The physical attributes of the path 353 are derived values from test data, e.g., empirical modeling data, etc. Examples of physical attributes of the path 353 include capacitances, inductances, a combination thereof, etc., of elements on the path 353. As described above, the capacitances and/or inductances of elements along the path 353 affect voltages and currents empirically determined using the projection method at the point on the path 353 and in turn, affect the coefficients of the characterized values and the constant of the characterized values.

[00175] In some embodiments, a function used to determine a wafer bias is a polynomial.

[00176] Figure 17 is a flowchart of an embodiment of the method 363 for determining a wafer bias at a model node of the system 126 (Figure 1). Figure 17 is described with reference to Figures 1 and 16. The method 363 is executed by the processor of the host system 130 (Figure 1). In an operation 365, one or more complex voltages and currents are received by the host system 130 from one or more communication devices of a generator system, which includes one or more of the x MHz RF generator, the y MHz RF generator, and the z MHz RF generator. For example, complex voltage and current measured at the node N3 is received from the communication device 185 (Figure 1). As another example, complex voltage and current measured at the node N5 is received from the communication device 189 (Figure 1). As yet another example, complex voltage and current measured at the node N3 and complex voltage and current measured at the node N5 are

received. It should be noted that an output of the generator system includes one or more of the nodes N3, N5, and an output node of the z MHz RF generator.

[00177] In an operation 367, based on the one or more complex voltages and currents at the output of the generator system, a projected complex voltage and current is determined at a point along, e.g., on, etc., the path 353 (Figure 16) between the impedance matching model 104 and the ESC model 125 (Figure 16). For example, the complex voltage and current at the output of the generator system is projected via the impedance matching model 104 (Figure 16) to determine a complex voltage and current at the model node N4m. As another example, the complex voltage and current at the output of the generator system is projected via the impedance matching model 104 and the portion 173 (Figure 1) of the RF transmission model 161 to determine a complex voltage and current at the model node N1m (Figure 1). As yet another example, the complex voltage and current at the output of the generator system is projected via the impedance matching model 104 and the RF transmission model 161 to determine a complex voltage and current at the model node N2m (Figure 1). As another example, the complex voltage and current at the output of the generator system is projected via the impedance matching model 104, the RF transmission model 161, and the ESC model 125 to determine a complex voltage and current at the model node N6m (Figure 1).

[00178] In an operation 369, a wafer bias is calculated at the point along the path 353 by using the projected complex V&I as an input to a function. For example, when the x, y, or z MHz RF generator is on and the remaining of the x, y, and z MHz RF generators are off, a wafer bias at the point is determined from a function, which is as a sum of a first product $a*V$, a second product $b*I$, a third product $c*\sqrt{P}$, and a constant d, where, V is a voltage magnitude of the projected complex voltage and current at the point, I is a current magnitude of the projected complex voltage and current at the point, P is a power magnitude of the projected complex voltage and current at the point, a, b, and c are coefficients, and d is a constant.

[00179] As another example, when two of the x, y, and z MHz RF generators are on and the remaining of the x, y, and z MHz RF generators are off, a wafer bias at the point is determined as a sum of a first product $a12*V1$, a second product $b12*I1$, a third product $c12*\sqrt{P1}$, a fourth product $d12*V2$, a fifth product $e12*I2$, a sixth product $f12*\sqrt{P2}$, and a constant g12, where V1 is a voltage magnitude at the point as a result of a first one of the two RF generators being on, I1 is a current magnitude at the point as a result of the first

RF generator being on, P_1 is a power magnitude at the point as a result of the first RF generator being on, V_2 is a voltage magnitude at the point as a result of a second one of the two RF generators being on, I_2 is a current magnitude at the point as a result of the second RF generator being on, and P_2 is a power magnitude at the point as a result of the second RF generator being on, a_{12} , b_{12} , c_{12} , d_{12} , e_{12} , and f_{12} are coefficients, and g_{12} is a constant.

[00180] As yet another example, when all of the x , y , and z MHz RF generators are on, a wafer bias at the point is determined as a sum of a first product $a_{123} \cdot V_1$, a second product $b_{123} \cdot I_1$, a third product $c_{123} \cdot \sqrt{P_1}$, a fourth product $d_{123} \cdot V_2$, a fifth product $e_{123} \cdot I_2$, a sixth product $f_{123} \cdot \sqrt{P_2}$, a seventh product $g_{123} \cdot V_3$, an eighth product $h_{123} \cdot I_3$, a ninth product $i_{123} \cdot \sqrt{P_3}$, and a constant j_{123} , where V_1 , I_1 , P_1 , V_2 , I_2 , and P_2 are described above in the preceding example, V_3 is a voltage magnitude at the point as a result of a third one of the RF generators being on, I_3 is a current magnitude at the point as a result of the third RF generator being on, and P_3 is a power magnitude at the point as a result of the third RF generator being on, a_{123} , b_{123} , c_{123} , d_{123} , e_{123} , f_{123} , g_{123} , h_{123} , and i_{123} are coefficients, and j_{123} is a constant.

[00181] Figure 18 is a block diagram of an embodiment of a system 330 that is used to illustrate advantages of determining wafer bias by using the method 340 (Figure 13), the method 351 (Figure 15), or the method 363 (Figure 17) instead of by using a voltage probe 332, e.g., a voltage sensor, etc.

[00182] The voltage probe 332 is coupled to the node N_1 to determine a voltage at the node N_1 . In some embodiments, the voltage probe 332 is coupled to another node, e.g., node N_2 , N_4 , etc., to determine voltage at the other node. The voltage probe 332 includes multiple circuits, e.g., an RF splitter circuit, a filter circuit 1, a filter circuit 2, a filter circuit 3, etc.

[00183] Also, the x and y MHz RF generators are coupled to a host system 334 that includes a noise or signal determination module 336. It should be noted that a module may be a processor, an ASIC, a PLD, a software executed by a processor, or a combination thereof.

[00184] The voltage probe 332 measures a voltage magnitude, which is used by the host system 334 to determine a wafer bias. The module 336 determines whether the voltage magnitude measured by the voltage probe 332 is a signal or noise. Upon determining that the

voltage magnitude measured by the voltage probe 332 is a signal, the host system 334 determines wafer bias.

[00185] The system 126 (Figure 1) is cost effective compared to the system 330 and saves time and effort compared to the system 330. The system 330 includes the voltage probe 332, which does not need to be included in the system 126. There is no need to couple a voltage probe at the node N4, N1, or N2 of the system 126 to determine wafer bias. In the system 126, wafer bias is determined based on the impedance matching model 104, RF transmission model 161, and/or the ESC model 125 (Figure 1). Moreover, the system 330 includes the module 336, which also does not need to be included in the system 126. There is no need to spend time and effort to determine whether a complex voltage and current is a signal or noise. No such determination needs to be made by the host system 130 (Figure 1).

[00186] Figures 19A, 19B, and 19C show embodiments of graphs 328, 332, and 336 to illustrate a correlation, e.g., a linear correlation, etc., between voltage, e.g., peak voltage, etc., that is measured at the output, e.g., the node N1, of the portion 195 (Figure 1) by using a voltage probe and a voltage, e.g., peak voltage, etc., at a corresponding model node output, e.g., the node N1m, determined using the method 102 (Figure 2). In each graph 328, 332, and 336, the measured voltage is plotted on a y-axis and the voltage determined using the method 102 is plotted on an x-axis.

[00187] Moreover, Figures 19A, 19B, and 19C show embodiments of graphs 330, 334, and 338 to illustrate a correlation, e.g., a linear correlation, etc., between wafer bias that is measured at the output N6 (Figure 1) by using a wafer bias probe and wafer bias at a corresponding model node output, e.g., the node N6m, determined using the method 340 (Figure 13), the method 351 (Figure 15), or the method 363 (Figure 17). In each graph 330, 334, and 338, the wafer bias determined using the wafer bias probe is plotted on a y-axis and the wafer bias determined using the method 340, the method 351, or the method 363 is plotted on an x-axis.

[00188] The voltages and wafer bias are plotted in the graphs 328 and 330 when the y MHz and z MHz RF generators are on and the x MHz RF generator is off. Moreover, the voltages and wafer bias are plotted in the graphs 332 and 334 when the x MHz and z MHz RF generators are on and the y MHz RF generator is off. Also, the voltages are plotted in the graphs 336 and 338 when the x MHz and y MHz RF generators are on and the z MHz RF generator is off.

[00189] Figure 20A is a diagram of an embodiment of graphs 276 and 278 to illustrate that there is a correlation between a wired wafer bias measured using a sensor tool, e.g., a metrology tool, a probe, a sensor, a wafer bias probe, etc., a model wafer bias that is determined using the method 340 (Figure 13), the method 351 (Figure 15), or the method 363 (Figure 17), and an error in the model bias. The wired wafer bias that is plotted in the graph 276 is measured at a point, e.g., a node on the RF transmission line 113, a node on the upper surface 183 (Figure 1) of the ESC 177, etc. and the model bias that is plotted in the graph 276 is determined at the corresponding model point, e.g., the model node N4m, the model node N1m, the model node N2m, the model node N6m, etc. (Figure 1), on the path 353 (Figure 16). The wired wafer bias is plotted along a y-axis in the graph 276 and the model bias is plotted along an x-axis in the graph 276.

[00190] The wired wafer bias and the model bias are plotted in the graph 276 when the x MHz RF generator is on, and the y and z MHz RF generators are off. Moreover, the model bias of graph 276 is determined using an equation $a2 \cdot V2 + b2 \cdot I2 + c2 \cdot \sqrt{P2} + d2$, where "*" represents multiplication, "sqrt" represents a square root, "V2" represents voltage at the point along the path 353 (Figure 16), I2 represents current at the point, P2 represents power at the point, "a2" is a coefficient, "b2" is a coefficient, "c2" is a coefficient, and "d2" is a constant value.

[00191] The graph 278 plots an error, which is an error in the model bias at the point, on a y-axis and plots the model bias at the point on an x-axis. The model error is an error, e.g., a variance, a standard deviation, etc., in the model bias. The model error and the model bias are plotted in the graph 278 when the x MHz RF generator is on and the y and z MHz RF generators are off.

[00192] Figure 20B is a diagram of an embodiment of graphs 280 and 282 to illustrate that there is a correlation between a wired wafer bias, a model bias that is determined using the method 340 (Figure 13), the method 351 (Figure 15) or method 363 (Figure 17), and an error in the model bias. The graphs 280 and 282 are plotted in a manner similar to the graphs 276 and 278 (Figure 17A) except that the graphs 280 and 282 are plotted when the y MHz RF generator is on and the x and z MHz RF generators are off. Moreover, the model bias of the graphs 280 and 282 is determined using an equation $a27 \cdot V27 + b27 \cdot I27 + c27 \cdot \sqrt{P27} + d27$, where "V27" represents a voltage magnitude at the point along the path 353 (Figure 16), "I27" represents a current magnitude at the point, "P27"

represents a power magnitude at the point, "a27" is a coefficient, "b27" is a coefficient, "c27" is a coefficient, and "d27" is a constant value.

[00193] Figure 20C is a diagram of an embodiment of graphs 284 and 286 to illustrate that there is a correlation between a wired wafer bias, a model bias that is determined using the method 340 (Figure 13), the method 351 (Figure 15) or method 363 (Figure 17), and an error in the model bias. The graphs 284 and 286 are plotted in a manner similar to the graphs 276 and 278 (Figure 17A) except that the graphs 284 and 286 are plotted when the z MHz RF generator is on and the x and y MHz RF generators are off. Moreover, the model bias of the graphs 284 and 286 is determined using an equation $a60 \cdot V60 + b60 \cdot I60 + c60 \cdot \sqrt{P60} + d60$, where "V60" represents a voltage magnitude at the point along the path 353 (Figure 16), "I60" represents a current magnitude at the point, "P60" represents a power magnitude at the point, "a60" is a coefficient, "b60" is a coefficient, "c60" is a coefficient, and "d60" is a constant value.

[00194] Figure 20D is a diagram of an embodiment of graphs 288 and 290 to illustrate that there is a correlation between a wired wafer bias, a model bias that is determined using the method 340 (Figure 13), the method 351 (Figure 15) or method 363 (Figure 17), and an error in the model bias. The graphs 288 and 290 are plotted in a manner similar to the graphs 276 and 278 (Figure 20A) except that the graphs 288 and 290 are plotted when the x and y MHz RF generators are on, and the z MHz RF generator is off. Moreover, the model bias of the graphs 288 and 290 is determined using an equation $a227 \cdot V2 + b227 \cdot I2 + c227 \cdot \sqrt{P2} + d227 \cdot V27 + e227 \cdot I27 + f227 \cdot \sqrt{P27} + g227$, where "a227", "b227" and "c227", "d227", "e227" and "f227" are coefficients, and "g227" is a constant value.

[00195] Figure 20E is a diagram of an embodiment of graphs 292 and 294 to illustrate that there is a correlation between a wired wafer bias, a model bias that is determined using the method 340 (Figure 13), the method 351 (Figure 15) or method 363 (Figure 17), and an error in the model bias. The graphs 292 and 294 are plotted in a manner similar to the graphs 276 and 278 (Figure 20A) except that the graphs 292 and 294 are plotted when the x and z MHz RF generators are on, and the y MHz RF generator is off. Moreover, the model bias of the graphs 292 and 294 is determined using an equation $a260 \cdot V2 + b260 \cdot I2 + c260 \cdot \sqrt{P2} + d20 \cdot V60 + e260 \cdot I60 + f260 \cdot \sqrt{P60} + g260$, where "a260", "b260", "c260", "d260", "e260" and "f260" are coefficients, and "g260" is a constant value.

[00196] Figure 20F is a diagram of an embodiment of graphs 296 and 298 to illustrate that there is a correlation between a wired wafer bias, a model bias that is determined using the method 340 (Figure 13), the method 351 (Figure 15) or method 363 (Figure 17), and an error in the model bias. The graphs 296 and 298 are plotted in a manner similar to the graphs 276 and 278 (Figure 20A) except that the graphs 296 and 298 are plotted when the y and z MHz RF generators are on, and the x MHz RF generator is off. Moreover, the model bias of the graphs 296 and 298 is determined using an equation $a_{2760} \cdot V_{27} + b_{2760} \cdot I_{27} + c_{2760} \cdot \sqrt{P_{27}} + d_{2760} \cdot V_{60} + e_{2760} \cdot I_{60} + f_{2760} \cdot \sqrt{P_{60}} + g_{2760}$, where "a2760", "b2760", "c2760", "d2760", "e2760" and "f2760" are coefficients, and "g2760" is a constant value.

[00197] Figure 20G is a diagram of an embodiment of graphs 302 and 304 to illustrate that there is a correlation between a wired wafer bias, a model bias that is determined using the method 340 (Figure 13), the method 351 (Figure 15) or method 363 (Figure 17), and an error in the model bias. The graphs 302 and 304 are plotted in a manner similar to the graphs 276 and 278 (Figure 20A) except that the graphs 302 and 304 are plotted when the x, y and z MHz RF generators are on. Moreover, the model bias of the graphs 302 and 304 is determined using an equation $a_{22760} \cdot V_2 + b_{22760} \cdot I_2 + c_{22760} \cdot \sqrt{P_2} + d_{22760} \cdot V_{60} + e_{22760} \cdot I_{60} + f_{22760} \cdot \sqrt{P_{60}} + g_{22760} \cdot V_{27} + h_{22760} \cdot I_{27} + i_{22760} \cdot \sqrt{P_{27}} + j_{22760}$, where "a22760", "b22760", "c22760", "d22760", "e22760", "f22760", "g22760", "h22760", and "i22760" are coefficients and "j22760" is a constant value.

[00198] Figure 21 is a block diagram of an embodiment of the host system 130. The host system 130 includes a processor 168, the storage HU 162, an input HU 380, an output HU 382, an input/output (I/O) interface 384, an I/O interface 386, a network interface controller (NIC) 388, and a bus 390. The processor 168, the storage HU 162, the input HU 380, the output HU 382, the I/O interface 384, the I/O interface 386, and the NIC 388 are coupled with each other via a bus 392. Examples of the input HU 380 include a mouse, a keyboard, a stylus, etc. Examples of the output HU 382 include a display, a speaker, or a combination thereof. The display may be a liquid crystal display, a light emitting diode display, a cathode ray tube, a plasma display, etc. Examples of the NIC 388 include a network interface card, a network adapter, etc.

[00199] Examples of an I/O interface include an interface that provides compatibility between pieces of hardware coupled to the interface. For example, the I/O interface 384 converts a signal received from the input HU 380 into a form, amplitude, and/or

speed compatible with the bus 392. As another example, the I/O interface 386 converts a signal received from the bus 392 into a form, amplitude, and/or speed compatible with the output HU 382.

[00200] It should be noted that in some embodiments, wafer bias is used to determine a clamping voltage that is used to clamp the work piece 131 (Figure 1) to the ESC 177 (Figure 1). For example, when wafer bias is absent from the plasma chamber 175 (Figure 1), two electrodes within the ESC 177 have matching voltages with opposite polarities to clamp the work piece 131 to the ESC 177. In the example, when the wafer bias is present within the plasma chamber 175, voltages supplied to the two electrodes are different in magnitude to compensate for the presence of the wafer bias. In various embodiments, wafer bias is used to compensate for bias at the ESC 177 (Figure 1).

[00201] It is also noted that the use of three parameters, e.g., current magnitude, voltage magnitude, and phase between the current and voltage, etc., to determine wafer bias compared to use of voltage to compensate for bias at the ESC 177 allows better determination of wafer bias. For example, wafer bias calculated using the three parameters has a stronger correlation to non-linear plasma regimes compared to a relation between RF voltage and the non-linear plasma regimes. As another example, wafer bias calculated using the three parameters is more accurate than that determined using a voltage probe.

[00202] It is further noted that although the above-described operations are described with reference to a parallel plate plasma chamber, e.g., a capacitively coupled plasma chamber, etc., in some embodiments, the above-described operations apply to other types of plasma chambers, e.g., a plasma chamber including an inductively coupled plasma (ICP) reactor, a transformer coupled plasma (TCP) reactor, conductor tools, dielectric tools, a plasma chamber including an electron-cyclotron resonance (ECR) reactor, etc. For example, the x MHz RF generator and the y MHz RF generator are coupled to an inductor within the ICP plasma chamber.

[00203] It is also noted that although the operations above are described as being performed by the processor of the host system 130 (Figure 1), in some embodiments, the operations may be performed by one or more processors of the host system 130 or by multiple processors of multiple host systems.

[00204] It should be noted that although the above-described embodiments relate to providing an RF signal to the lower electrode of the ESC 177 (Figures 1 and 18) and to the

lower electrode of the ESC 192 (Figure 11), and grounding the upper electrodes 179 and 264 (Figures 1 and 11), in several embodiments, the RF signal is provided to the upper electrodes 179 and 264 while the lower electrodes of the ESCs 177 and 192 are grounded.

[00205] Embodiments described herein may be practiced with various computer system configurations including hand-held hardware units, microprocessor systems, microprocessor-based or programmable consumer electronics, minicomputers, mainframe computers and the like. The embodiments can also be practiced in distributed computing environments where tasks are performed by remote processing hardware units that are linked through a network.

[00206] With the above embodiments in mind, it should be understood that the embodiments 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 relates 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.

[00207] One or more embodiments can also 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-ROMs (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.

[00208] Although the method operations in the flowchart of Figure 2, Figure 13, Figure 15, and Figure 17 above were described in a specific order, it should be understood that other housekeeping operations may be performed in between operations, or operations may be adjusted so that they occur at slightly different times, or may be distributed in a system which allows the occurrence of the processing operations at various intervals associated with the processing, as long as the processing of the overlay operations are performed in the desired way.

[00209] One or more features from any embodiment may be combined with one or more features of any other embodiment without departing from the scope described in various embodiments described in the present disclosure.

[00210] Although the foregoing embodiments have been described in 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. Accordingly, the present embodiments are to be considered as illustrative and not restrictive, and the embodiments are not to be limited to the details given herein, but may be modified within the scope and equivalents of the appended claims.

CLAIMS

1. A method for determining wafer bias, the method comprising:
 - detecting output of a generator to identify a generator output complex voltage and current, the generator coupled to an impedance matching circuit, the impedance matching circuit coupled via a radio frequency (RF) transmission line to an electrostatic chuck (ESC) of a plasma chamber;
 - determining from the generator output complex voltage and current a projected complex voltage and current at a point along a path between an output of a model of the impedance matching circuit and a model of the ESC, the determining of the projected complex voltage and current performed using a model for at least part of the path, the model for at least part of the path characterizing physical components along the path; and
 - applying the projected complex voltage and current as an input to a function to map the projected complex voltage and current to a wafer bias value at the ESC model.
2. The method of claim 1, wherein the function is characterized by a summation of values that represent physical attributes of the path, wherein the projected complex voltage and current is used in the summation of the values.
3. The method of claim 2, wherein the physical attributes of the path are derived values from test data.
4. The method of claim 1, wherein the function is a sum of characterized values and a constant, the characterized values including magnitudes and coefficients, the magnitudes derived from the projected complex voltage and current, the coefficients and the constant incorporating empirical modeling data.
5. The method of claim 4, wherein the coefficients are coefficients of the magnitudes.

6. The method of claim 4, wherein the empirical modeling data includes data obtained based on measurements of wafer bias at the ESC, based on determinations of magnitudes of complex voltages and currents, and based on an application of estimation statistical method to the measurements of the wafer bias at the ESC and the magnitudes of complex voltage and current, the determination of the magnitudes of complex voltages and currents made based on the impedance matching model and the model for at least part of the path.
7. The method of claim 1, wherein the function includes a sum of a first product, a second product, a third product, and a constant, wherein the first product is a product of a coefficient and a voltage magnitude, the second product is a product of a coefficient and a current magnitude, the third product is a product of a coefficient and a square root of power, the voltage magnitude extracted from the projected complex voltage and current, the current magnitude extracted from the projected complex voltage and current, the power magnitude calculated from the current magnitude and the voltage magnitude.
8. A method for determining wafer bias, the method comprising:
 - receiving one or more generator output complex voltages and currents measured at one or more outputs of one or more generators, the one or more generators coupled to an impedance matching circuit, the impedance matching circuit coupled via a radio frequency (RF) transmission line to an electrostatic chuck (ESC) of a plasma chamber;
 - determining from the one or more complex voltages and currents projected complex voltage and current at a point along a path between a model of the impedance matching circuit and a model of the ESC, the models characterizing physical components along the path; and
 - calculating a wafer bias at the point by using the projected complex voltage and current as an input to a function.
9. The method of claim 8, wherein the function is characterized by a summation of values that represent physical attributes of the path, wherein the projected complex voltage and current is used in the summation of the values.

10. The method of claim 9, wherein the physical attributes of the path are derived values from test data.
11. The method of claim 8, wherein the function is a sum of characterized values and a constant, the characterized values including magnitudes and coefficients, the magnitudes derived from the projected complex voltage and current, the coefficients and the constant incorporating empirical modeling data.
12. The method of claim 11, wherein the coefficients are coefficients of the magnitudes.
13. The method of claim 11, wherein the empirical modeling data includes data obtained based on measurements of wafer bias at the ESC, based on determinations of magnitudes of complex voltages and currents, and based on an application of estimation statistical method to the measurements of the wafer bias at the ESC and the magnitudes of complex voltage and current, the determination of the magnitudes of complex voltages and currents made based on the impedance matching model and the model for at least part of the path.
14. The method of claim 8, wherein the function includes a sum of a first product, a second product, a third product, and a constant, wherein the first product is a product of a coefficient and a voltage magnitude, the second product is a product of a coefficient and a current magnitude, the third product is a product of a coefficient and a square root of power, the voltage magnitude identified from the projected complex voltage and current, the current magnitude identified from the projected complex voltage and current, the power magnitude determined from the current magnitude and the voltage magnitude.
15. A method for determining wafer bias, the method comprising:
 - identifying a first complex voltage and current measured at an output of a radio frequency (RF) generator when the RF generator is coupled to a plasma chamber via an impedance matching circuit, the impedance matching circuit having an input coupled to the output of the RF generator and an output coupled to an RF transmission line;

generating an impedance matching model based on electrical components defined in the impedance matching circuit, the impedance matching model having an input and an output, the input of the impedance matching model receiving the first complex voltage and current, the impedance matching model having one or more elements;

propagating the first complex voltage and current through the one or more elements from the input of the impedance matching model to the output of the impedance matching model to determine a second complex voltage and current, wherein the second complex voltage and current is at the output of the impedance matching model; and

determining a wafer bias based on a voltage magnitude of the second complex voltage and current, a current magnitude of the second complex voltage and current, and a power magnitude of the second complex voltage and current.

16. The method of claim 15, wherein determining the wafer bias comprises:

calculating the power magnitude based on the voltage magnitude and the current magnitude; and

calculating a sum of a first product, a second product, a third product, and a constant, wherein the first product is of the voltage magnitude and a first coefficient, the second product is of the current magnitude and a second coefficient, and the third product is of a square root of the power magnitude and a third coefficient.

17. The method of claim 15, wherein determining the wafer bias is performed based on whether the RF generator is on.

18. The method of claim 15, further comprising:

generating an RF transmission model based on circuit components defined in the RF transmission line, the RF transmission model having an input and an output, the input of the RF transmission model coupled to the output of the impedance matching model, the RF transmission model having a portion, wherein the wafer bias is determined at the output of the RF transmission model portion.

19. The method of claim 15, further comprising:

generating an RF transmission model based on electrical components defined in the RF transmission line, the RF transmission model having an input and an output, the input of the RF transmission model coupled to the output of the impedance matching model, wherein the wafer bias is determined at the output of the RF transmission model.

20. The method of claim 19, wherein the electrical components of RF transmission line include capacitors, inductors, or a combination thereof, the RF transmission model including one or more elements, wherein the elements of the RF transmission model have similar characteristics as that of the electrical components of the RF transmission line.
21. The method of claim 15, wherein the first complex voltage and current received is measured at the output of the RF generator with a voltage and current probe, the voltage and current probe calibrated according to a pre-set formula.
22. The method of claim 21, wherein the pre-set formula is a standard.
23. The method of claim 22, wherein the standard is a National Institute of Standards and Technology (NIST) standard, wherein the voltage and current probe is coupled with an open circuit, a short circuit, or a load to calibrate the voltage and current probe to comply with the NIST standard.
24. The method of claim 15, wherein the second complex voltage and current includes a voltage value, a current value, and a phase between the voltage value and the current value.
25. The method of claim 15, wherein the elements of the impedance matching model include capacitors, inductors, or a combination thereof, wherein the electrical components of impedance matching circuit include capacitors, inductors, or a combination thereof, wherein the elements of the impedance matching model have similar characteristics as that of the electrical components of the impedance matching circuit.

26. The method of claim 15, wherein the wafer bias is for use in a system, wherein the system includes an RF transmission line and excludes a voltage probe on the RF transmission line.
27. The method of claim 15, further comprising:
generating an RF transmission model based on electrical components defined in the RF transmission line, the RF transmission model having an input and an output, the input of the RF transmission model coupled to the output of the impedance matching model;
and
generating an electrostatic chuck (ESC) model based on characteristics of an electrostatic chuck of the plasma chamber, the ESC model having an input, the input of the ESC model coupled to the output of the RF transmission model, wherein the wafer bias is determined at the output of the ESC model.
28. The method of claim 15, wherein propagating the first complex voltage and current through the one or more elements from the input of the impedance matching model to the output of the impedance matching model to determine the second complex voltage and current comprises:
determining an intermediate complex voltage and current within an intermediate node within the impedance matching model based on the first complex voltage and current and characteristics of one or more elements of the impedance matching model coupled between the input of the impedance matching model and the intermediate node; and
determining the second complex voltage and current based on the intermediate complex voltage and current and characteristics of one or more elements of the impedance matching model coupled between the intermediate node and the output of the impedance matching model.
29. The method of claim 15, wherein the RF transmission model includes a model of an RF tunnel and a model of an RF strap, the RF tunnel model coupled with the RF strap model.
30. A plasma system for determining wafer bias, comprising:

one or more radio frequency (RF) generators for generating one or more RF signals, the one or more RF generators associated with one or more voltage and current probes, wherein the one or more voltage and current probes are configured to measure one or more complex voltages and currents at corresponding one or more outputs of the one or more RF generators;

an impedance matching circuit coupled to the one or more RF generators;

a plasma chamber coupled to the impedance matching circuit via an RF transmission line, the plasma chamber including an electrostatic chuck (ESC), the ESC coupled to the RF transmission line; and

a processor coupled to the one or more RF generators, the processor configured to:

receive the one or more complex voltages and currents;

determine from the one or more complex voltages and currents projected complex voltage and current at a point along a path between a model of the impedance matching circuit and a model of the ESC, the models characterizing physical components along the path; and

calculate a wafer bias at the point by using the projected complex voltage and current as an input to a function.

31. The method of claim 30, wherein the function is characterized by a summation of values that represent physical attributes of the path, wherein the projected complex voltage and current is used in the summation of the values.
32. The method of claim 31, wherein the physical attributes of the path are derived values from test data.
33. The method of claim 30, wherein the function is a sum of characterized values and a constant, the characterized values including magnitudes and coefficients, the magnitudes derived from the projected complex voltage and current, the coefficients and the constant incorporating empirical modeling data.
34. The method of claim 33, wherein the coefficients are coefficients of the magnitudes.

35. The method of claim 33, wherein the empirical modeling data includes data obtained based on measurements of wafer bias at the ESC, based on determinations of magnitudes of complex voltages and currents, and based on an application of estimation statistical method to the measurements of the wafer bias at the ESC and the magnitudes of complex voltage and current, the determination of the magnitudes of complex voltages and currents made based on the impedance matching model and the model for at least part of the path.
36. The plasma system of claim 30, wherein the function includes a sum of a first product, a second product, a third product, and a constant, wherein the first product is a product of a coefficient and a voltage magnitude, the second product is a product of a coefficient and a current magnitude, the third product is a product of a coefficient and a square root of power, the voltage magnitude extracted from the projected complex voltage and current, the current magnitude extracted from the projected complex voltage and current, the power magnitude calculated from the current magnitude and the voltage magnitude.