

one or more parts, e.g., the x MHz RF generator, the y MHz RF generator, communication mediums 110 and 196, etc., of the plasma system 104 that are coupled to the impedance matching network 112 on another side. In one embodiment, the impedance matching network 112 is tuned to facilitate a match between an impedance of the load with an impedance of the source. An impedance match between a load and a source reduces chances of power being reflected from the load towards the source. Examples of a communication medium include an RF rod, a cable, a wire, an RF strap, or any other conductive device that facilitates transfer of an RF signal.

[0039] The plasma chamber 114 includes an electrostatic chuck (ESC) 146, an upper electrode 194, and other parts (not shown), e.g., an upper dielectric ring surrounding the upper electrode 194, an upper electrode extension surrounding the upper dielectric ring, a lower dielectric ring surrounding a lower electrode of the ESC 146, a lower electrode extension surrounding the lower dielectric ring, an upper plasma exclusion zone (PEZ) ring, a lower PEZ ring, etc. The upper electrode 194 is located opposite to, on top of, and facing the ESC 146. A work piece 119, e.g., a substrate, etc., is supported on an upper surface ~~427~~125 of the ESC 146. An example of a substrate includes a semiconductor wafer. Another example of a substrate includes a wafer on which electrical circuitry, e.g., circuitry including transistors, resistors, capacitors, logic gates, etc., is fabricated. Integrated circuits, e.g., application specific integrated circuit (ASIC), programmable logic device (PLD), etc. are developed on the work piece 119 and the integrated circuits are used in a variety of electronic devices, e.g., cell phones, tablets, smart phones, computers, laptops, networking equipment, etc. Each of the upper electrode 194 and the lower electrode is made of a metal, e.g., aluminum, alloy of aluminum, copper, etc.

[0040] In one embodiment, the upper electrode 194 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.

[0041] In some embodiments, the upper electrode 194 is grounded.

[0042] The ESC 146 is coupled to the x MHz RF generator and the y MHz RF generator via the impedance matching network 112, the RF transmission line 150, and communication mediums 110 and 196. The RF transmission line 150 includes one or more

communication mediums, e.g., RF rods, RF straps, cables, wires, connectors, or a combination thereof, etc., to transfer an RF signal between the impedance matching network 112 and the plasma chamber 114.

[0043] When the process gas is supplied between the upper electrode 194 and the ESC 146 and when the x MHz RF generator and/or the y MHz RF generator supplies power via the impedance matching network 112 to the ESC 146, the process gas is ignited to generate plasma within the plasma chamber 114.

[0044] The host system 180 generates a digital pulsing signal 122 that has two states S1 and S0. In one embodiment, a state associated with the plasma system 104 is the same as the state of the digital pulsing signal 122. As an example, the digital pulsing signal 122 has a 50% duty cycle, one for a state. As another example, the digital pulsing signal 122 has a duty cycle other than 50%. In this example, the higher duty cycle is for one state and the lower duty cycle is for another state. In one embodiment, instead of using the host system 180 to generate the digital pulsing signal 122+12, a clock source, e.g., an oscillator, is used to generate a clock signal, which is an example of the digital pulsing signal 122.

[0045] The digital pulsing signal 122 is sent by the host system 180 to a digital signal processor (DSP) 166 of the x MHz RF generator and to a DSP 178 of the y MHz RF generator. Examples of a processor include an ASIC, a PLD, a microprocessor, a microcontroller, a central processing unit (CPU), etc.

[0046] Upon receiving the digital pulsing signal 122+12, each DSP 166 and 178 determines whether a state of the digital pulsing signal 122+12 is S1 or S0. For example, the DSP 166 distinguishes between the states S0 and S1. As another example, the DSP 166 determines that the digital pulsing signal 122 has a first magnitude, e.g., the value of 1, the high value, etc., during a first set of time periods and has a second magnitude, e.g., the value of 0, the low value, etc., during a second set of time periods. The DSP 166 determines that the digital pulsing signal 122 has the state S1 during the first set of time periods and has the state S0 during the second set of time periods. As yet another example, the DSP 166 compares a magnitude of the digital pulsing signal 122 with a pre-stored value to determine that the magnitude of the digital pulsing signal 122 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 122 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 166 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.

[0047] When the state associated with the pPlasma system 104102 is S1, the DSP 166 generates a parameter value Px1 and provides the parameter value Px1 to a parameter control 168 of the x MHz RF generator. Examples of a parameter include frequency, power, etc. Moreover, when the state associated with the pPlasma system 104102 is S1, a DSP 178 of the y MHz RF generator generates a parameter value Py1 and provides the parameter value Py1 to a parameter control 182 of the y MHz RF generator.

[0048] Similarly, when the state associated with the pPlasma system 104102 is S0, the DSP 166 generates a parameter value Px0 and provides the parameter value Px0 to a parameter control 170 of the x MHz RF generator. Also, when the state associated with the pPlasma system 104102 is S0, the DSP 178 generates a parameter value Py0 and provides the parameter value Py0 to a parameter control 184 of the y MHz RF generator.

[0049] It should be noted that in one embodiment, a parameter control of an RF generator is a portion of a computer program that is embodied within a computer-readable medium and that is executed by a DSP of the RF generator. For example, the parameter control 168 and the parameter control 170 are logic blocks, e.g., tuning loops, which are portions of a computer program that is executed by the DSP 166. As another example, the parameter control 182 and the parameter control 184 are logic blocks of a computer program that is executed by the DSP 178.

[0050] In some embodiments, a computer program is embodied within a non-transitory computer-readable medium, e.g., a storage device. Examples of a storage device include a read-only memory (ROM), a random access memory (RAM), or a combination thereof. To illustrate, a storage device includes a hard disk, a Flash memory, a redundant array of independent disks, etc.

[0051] In an embodiment, a hardware controller, e.g., a microcontroller, an ASIC, a PLD, etc., is used instead of a parameter control. For example, a controller is used instead of the parameter control 168176, another controller is used instead of the parameter control 170178, yet another controller is used instead of the parameter control 182, and another controller is used instead of the parameter control 184. In some embodiments, a hardware controller includes a processor and storage device.

[0057] Moreover, during the state S0 associated with the pPlasma system 104~~102~~, the parameter control 170 that is coupled to the DSP 166 and to the DAS 172 receives the parameter value Px0 from the DSP 166. Based upon the parameter value Px0, the x MHz RF generator generates an RF signal that is sent from the x MHz RF generator via the communication medium 110 to the impedance matching network 112. For example, the parameter control 170 looks-up a drive parameter value corresponding to the parameter value Px0 to provide to the driver 174. The driver 174 generates an RF signal having a drive parameter value and provides the RF signal to the amplifier 176. In one embodiment, the drive parameter value is the same as the parameter value Px0. The amplifier 176 may amplify the drive parameter value to generate an RF signal having an amplified parameter value, which may be the same as the drive parameter value of an RF signal that is received by the amplifier 176 from the driver 174. The RF signal having the amplified parameter value is supplied by the DAS 172 via the communication medium 196 to the impedance matching network 112.

[0058] Similarly, during the state S0 associated with the plasma system 104, the DAS 188 generates an RF signal that is sent via the communication medium 196 to the impedance matching network 112. The RF signals received from the x MHz RF generator and the y MHz RF generator are combined in the impedance matching network 112 to generate an RF signal 156 during the state S0. The RF signal 156 is provided via RF transmission line 150 to lower electrode of the ESC 146 of the plasma chamber 114.

[0059] It should be noted that in response to power supplied within the RF signal 154 and the RF signal 156, power is reflected from the plasma chamber 114 towards the x MHz RF generator and the y MHz RF generator. For example, in response to forward power supplied within the RF signals 154 and 156, power is reflected from the plasma chamber 114 via the RF transmission line 150, the impedance matching network 112, and the communication medium 110 to the x MHz RF generator. As another example, in response to supplied power within the RF signals 154 and 156, power is reflected from the plasma chamber 114 via the RF transmission line 150, the impedance matching network 112, and the communication medium 196 to the y MHz RF generator.

[0060] In some embodiments, forward power and supplied power are used interchangeably herein.

to use a bias compensation circuit to measure the wafer bias. An example of the bias compensation circuit includes a silicon carbide pin.

[0082] In some embodiments, instead of the peak magnitude used to determine the ion energy, a root mean square magnitude is used.

[0083] In various embodiments, when multiple RF generators are on, the peak magnitude used to determine the ion energy is a peak voltage of a statistical value, e.g., median, mean, etc., of peak RF voltages of the RF generators that are on. For example, the V_{peak} is an average of peak magnitudes that are measured by the voltage and current probes 152 and 186 at the outputs of the x and y MHz RF generators.

[0084] In one embodiment, the DC bias potential of the equation (1) is measured using the bias compensation circuit, e.g., a DC sensor, etc. For example, the bias compensation circuit may be immersed in the plasma of the plasma chamber 114 (Figure 2) to measure the DC bias potential. In various embodiments, the DC sensor is coupled to the communication medium 110 or the RF transmission line 150 to measure the DC bias potential.

[0085] In embodiments in which the x MHz RF generator is operational, e.g., is on, is not malfunctioning, is functioning, is on, etc., and the y MHz RF generator is inoperational, e.g., is off, is malfunctioning, is not operating, etc., the DC bias potential of the equation (1) is determined by a processor of the plasma system 104 according to an equation:

$$a_x * V_x + b_x * I_x + c_x * \sqrt{P_x} + d_x \quad \dots (12)$$

where "*" represents multiplication, "sqrt" is a square root, " V_x " represents a voltage magnitude at a model node, " I_x " represents a current magnitude at the model node, " P_x " represents a magnitude of power at the model node, " a_x " is a coefficient, " b_x " is a coefficient, " c_x " is a coefficient, and " d_x " represents a constant value. In some embodiments, a power magnitude used to determine the wafer bias at a model node is a product of a voltage magnitude at the model node, a current magnitude at the model node, and a cosine of a phase between the voltage magnitude and the current magnitude. In various embodiments, a power magnitude is a magnitude of delivered power, which includes a difference between forward power and reflected power. The coefficients a_x , b_x , and c_x , and the constant d_x are stored within a storage device of the host system 180 (Figure 2).

[0086] In embodiments in which the x MHz RF generator is operational and the y MHz RF generator is operational, the DC bias potential of the equation (1) is determined by a processor of the plasma system 104 according to an equation:

$$axy*Vx + bxy*Ix + cxy*\sqrt{Px} + dxy*Vy + exy*Iy + fxy*\sqrt{Py} + gxy \quad \dots(23)$$

where "*" represents multiplication, "Vx" represents a voltage magnitude at a model node, "Ix" represents a current magnitude at the model node, "Px" represents a magnitude of power at the model node, "Vy" represents a voltage magnitude at the model node, "Iy" represents a current magnitude at the model node, "Py" represents a magnitude of power at the model node, and each of "axy", "bxy", "cxy", "dxy", "exy", "fxy" is a coefficient, and "gxy" is a constant. In some embodiments, the voltage Vy at the model node is a result of propagating a complex voltage and current measured by the voltage and current probe 186 of the y MHz RF generator via a model of the communication medium 196 and via a model of a branch of the impedance matching network 112 that is coupled to the communication medium 196. It should be noted that in various embodiments, Py is a product of Vy, Iy, and a cosine of a phase between Vy and Iy. The coefficients axy, bxy, cxy, dxy, exy, fxy, and the constant gxy are stored within a storage device of the host system 180 (Figure 2).

[0087] In embodiments in the x MHz RF generator, the y MHz RF generator, and a z MHz RF generator are operational, the DC bias potential of the equation (1) is determined by a processor of the plasma system 104 according to an equation:

$$axyz*Vx + bxyz*Ix + cxyz*\sqrt{Px} + dxyz*Vy + exyz*Iy + fxyz*\sqrt{Py} + gxyz*Vz + hxyz*Iz + ixyz*\sqrt{Pz} + jxyz \quad \dots(34)$$

where "*" represents multiplication, "Vx" represents a voltage magnitude at a model node, "Ix" represents a current magnitude at the model node, "Px" represents a magnitude of power at the model node, "Vy" represents a voltage magnitude at the model node, "Iy" represents a current magnitude at the model node, "Py" represents a magnitude of power at the model node, "Vz" represents a voltage magnitude at the model node, "Iz" represents a current magnitude at the model node, "Pz" represents a magnitude of power at the model node, each of "axyz", "bxyz", "cxyz", "dxyz", "exyz", "fxyz", "gxyz", "hxyz", "ixyz" is a coefficient, and "jxyz" is a constant. In some embodiments, the voltage Vz at the model node is a result of propagating a complex voltage and current measured by a voltage and current probe of the z MHz RF generator via a model of an RF cable that is connected to the z MHz RF generator and via a model of a branch of the impedance matching network 112 that is

[00111] As yet another example, when ion energy within the plasma chamber 114 is to be enhanced compared to that during the state S0, the operations 108, 124, and 126 or the operations 108, 124, and 129 are performed during the state S1.

[00112] As another example, when a layer of material is to be deposited on the substrate 119, the operations 116, 118, and 131 or the operations 116, 118, and 127 are performed during the state S0 to facilitate deposition on the substrate 119. As another example, when the substrate 119 is to be etched at the lower rate, the operations 116, 118, and 131 or the operations 116, 118, and 127 are performed during the state S0 to facilitate etching of the substrate 119 at the lower rate. As yet another example, when material is to be deposited on the substrate 119 at the higher rate than a rate at which material is to be deposited on the substrate 119 during the state S1, the operations 116, 118, and 131 or the operations 116, 118, and 127 are performed during the state S0 to facilitate deposition on the substrate 119 at the higher rate. As yet another example, when ion energy within the plasma chamber 114 is to be neutralized, e.g., reduced, etc., the operations 116, 118, and 131 or the operations 116, 118, and 127 are performed during the state S0.

[00113] Figure 4 is a graph ~~133~~¹³⁴ that plots RF power that is provided by 2 MHz and 60 MHz RF generators to an electrode, e.g., the lower electrode, the upper electrode, etc., of a plasma chamber, e.g., the plasma chamber 114 (Figure 2), versus time. In a state 1, e.g., the state S1, RF power of an RF signal that is generated by the 2 MHz RF generator is greater than RF power of an RF signal that is generated by the 60 MHz RF generator. For example, RF power of the RF signal generated by the 2 MHz RF generator is 7 kilowatts (kW) and RF power of the RF signal generated by the 60 MHz RF generator is 1 kW. Also, during the state 1, both the RF generators are operated in a power control mode, which is an example of the first variable control mode 155 (Figure 1A). Moreover, during the state 1, etching is performed on a substrate, e.g., the substrate 119 (Figure 2), and the method operations 108, 124, and 126 or the operations 108, 124, and 129 are performed during the state S1 to optimize, e.g., increase, etc., ion energy and density of plasma within the plasma chamber 114. The optimization facilitates the etching.

[00114] In a state 0, e.g., the state S0, RF power of an RF signal that is generated by the 2 MHz RF generator is less than RF power of an RF signal that is generated by the 60 MHz RF generator. For example, RF power of the RF signal generated by the 2 MHz RF generator is 0 kW and RF power of the RF signal generated by the 60 MHz RF generator is less than 15 watts. Also, during the state 0, both the RF generators are operated in the second

[00128] Figure 7 is a flowchart of an embodiment of a method 191 for using ion energy for states associated with the plasma system 104 (Figure 2). The method 191 is described with reference to Figure 2. The method 191 is executed by one or more processors, e.g., a processor of the host system 180 (Figure 2), or the DSP 166, or the DSP 178 (Figure 2), or a combination of the processor of the host system 180 and the DSP 166, or a combination of the processor of the host system 180 and the DSP 178, etc.

[00129] The operation 106 is performed. Upon determining that the state associated with the plasma system 104 is the first state, in an operation 131, ion energy within the plasma chamber 114 is determined. The ion energy within the plasma chamber 114 during the first state is determined in a manner similar to determining ion energy within the plasma chamber 114 during the second state. For example, when the RF signal 154 (Figure 2) is transferred to the plasma chamber 114, the voltage and current probe 152 (Figure 2) measures the complex voltage and current at the communication medium 110 and provides the measured complex voltage and current to a processor of the host system 180 (Figure 2) via the DSP 166 (Figure 2). The complex voltage and current is propagated via one or more models of one or more parts of the plasma system 104 to calculate a complex voltage and current at a model node, e.g., an output of the one or more models, an input of a model, within a model etc. Based on the complex voltage and current at the model node, the processor of the host system 180 determines an ion energy. ~~In this example, the processor determines the ion energy using the equation (1).~~

[00130] On the other hand, upon determining that the state associated with the plasma system 104 is the second state, in an operation 139, ion energy is determined. The ion energy is determined in the operation 139 in a manner similar to determining the second variable during the operation 116 (Figure 3) except that the second variable is ion energy. ~~For example, the equation (1) is used to determine the ion energy.~~

[00131] Moreover, in an operation 140, it is determined whether the ion energy determined during the operation 139 meets a first ion energy threshold. For example, it is determined whether the ion energy determined during the operation 139 exceeds the first ion energy threshold. The operation 140 is similar to the operation 118 (Figure 3) except that the second variable is ion energy and the first threshold of the operation 118 is the first ion energy threshold. For example, it is determined whether the ion energy determined during the operation 139 exceeds the first ion energy threshold. The first ion energy threshold is

[00134] On the other hand, upon determining that the ion energy determined during the operation 139 is not less than the first ion energy threshold and does not exceed the first ion energy threshold, in an operation 145, an instruction is provided to maintain the power value Px0 in a manner similar to that described above with reference to the operation 131 (Figure 3). The method 191 repeats after the operation 145.

[00135] In an operation 132, it is determined whether the ion energy determined during the operation 141+34 meets a second ion energy threshold. For example, it is determined whether the ion energy determined during the operation 141+34 exceeds the second ion energy threshold. The second ion energy threshold is stored within a storage device, e.g., a storage device of the host system 180 or any other storage device of the plasma system 104.

[00136] Upon determining that the ion energy determined during the operation 141+34 exceeds the second ion energy threshold, in an operation 134, an instruction is provided to change power of the RF signal 154 (Figure 2). For example, upon determining that the ion energy determined during the operation 141+34 exceeds the second ion energy threshold, in the operation 134, an instruction is provided to reduce power of the RF signal 154. The operation 134 is similar to the operation 126 (Figure 3) except that the operation 134 is performed with respect to the second ion energy threshold and is performed with respect to the determined ion energy of operation 141+34. For example, processor of the host system 180 provides an instruction to the DSP 166 (Figure 2) to reduce power from the power value Px1 to a power value at which the ion energy determined during the operation 141+34 does not exceed the second ion energy threshold. As another example, the operations 106, 141+34, 132, and 134 are iteratively repeated until the power value Px1 is reduced to a value at which the ion energy determined during the operation 141+34 does not exceed the second ion energy threshold. As a further example, to iteratively determine the power value at which the ion energy determined during the operation 141+34 does not exceed the second ion energy threshold, the operation 106 is not repeated. Rather, the operations 141+34, 132, and 134 are iteratively repeated.

[00137] On the other hand, upon determining that the ion energy determined during the operation 141+34 does not exceed the second ion energy threshold, in the operation 132, it is determined whether the ion energy determined during the operation 141+34 is less than the second ion energy threshold. Upon determining that the ion energy determined during the operation 141+34 is less than the second ion energy threshold, in the operation 134, an instruction is provided by the processor of the host system 180 to increase the power value

Px1. The operation 134 is similar to the operation 126 (Figure 3) except that the operation 134 is performed with respect to the second ion energy threshold and with respect to the determined ion energy of operation ~~141~~~~131~~. For example, the processor of the host system 180 provides an instruction to the DSP 166 to increase power from the power value Px1 and the DSP 166 increases the power value Px1 to the power value "Px1+1". As another example, the operations 106, ~~141~~~~131~~, 132, and 134 are iteratively repeated until the power value Px1 is increased to a value at which the ion energy determined during the operation ~~141~~~~131~~ is not lower than the second ion energy threshold. As a further example, to iteratively determine the power value at which the ion energy determined during the operation ~~141~~~~131~~ is not less than the second ion energy threshold, the operation 106 is not repeated. Rather, the operations ~~141~~~~131~~, 132, and 134 are repeated. The method 191 is repeated after the operation 134.

[00138] On the other hand, upon determining that the ion energy determined during the operation ~~141~~~~131~~ is not less than the second ion energy threshold and does not exceed the second ion energy threshold, in an operation 137, an instruction is provided to maintain the power value Px1. For example, the processor of the host system 180 provides an instruction to the DSP 166 to continue to provide the power value Px1 to the parameter control 168. In one embodiment, the processor of the host system 180 provides the power value Px1 to the DSP 166 and the DSP 166 provides the power value Px1 to the parameter control 168. The method 191 repeats after the operation 137.

[00139] The use of ion energy in various embodiments of the present disclosure results in a low measured time between failures (MTBF).

[00140] Figure 8 is a block diagram of an embodiment of the host system 276, which is an example of the host system 180 (Figure 1). The host system 276 includes a processor 280, a storage device 278, an input device 266, an output device 268, an input/output (I/O) interface 270, an I/O interface 272, a network interface controller (NIC) 274, and a bus 275. The processor 280, the storage device 278, the input device 266, the output device 268, the I/O interface 270, the I/O interface 272, and the NIC 274 are coupled with each other via the bus 275. Examples of the input device 266 include a mouse, a keyboard, a stylus, etc. Examples of the output device 268 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 274 include a network interface card, a network adapter, etc.