

includes an upper electrode, e.g., an antenna, etc., coupled to the filter. The upper electrode faces the chuck and receives the filtered signal to facilitate achieving ion energy at the chuck to be between a lower threshold and an upper threshold.

[0010] A system for controlling ion energy within a plasma chamber is described. The system includes a first nonsinusoidal radio frequency (RF) generator for generating a first nonsinusoidal signal and a first power amplifier coupled to the first nonsinusoidal RF generator. The first power amplifier amplifies the first nonsinusoidal signal to generate a first amplified signal. The system includes a first filter coupled to the first power amplifier. The first filter filters the first amplified signal using a first filtering signal to generate a first filtered signal. The system includes an upper electrode coupled to the first filter, a second nonsinusoidal RF generator for generating a second nonsinusoidal signal, and a second power amplifier coupled to the second nonsinusoidal RF generator. The second power amplifier amplifies the second nonsinusoidal signal to generate a second amplified signal. The system includes a second filter coupled to the second power amplifier. The second filter filters the second amplified signal using a second filtering signal to generate a second filtered signal. The system includes a chuck coupled to the second filter. The chuck faces the upper electrode and includes a lower electrode. The lower electrode receives the second filtered signal to facilitate achieving the ion energy at the chuck to be between the lower threshold and the upper threshold. The upper electrode receives the first filtered signal to facilitate achieving ion energy at the chuck to be between a lower threshold and an upper threshold.

[0011] Some advantages of the above-described embodiments include confining ion energy between the upper and lower thresholds. The confinement is achieved with the use of a filtered amplified signal that is supplied to the chuck, a filtered amplified signal that is supplied to the surface antenna, or filtered amplified signals that are supplied to both the chuck and the surface antenna.

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

the nonsinusoidal RF generator 214 and the nonsinusoidal RF generator 214 generates the nonsinusoidal RF signal 218 having the power profile. It should be noted that power magnitude as a function of time includes a frequency of the nonsinusoidal RF signal 218.

[0077] In a number of embodiments, a power profile that is provided by the processor 126 to the nonsinusoidal RF generator 120 (Figure 1A) is different than a power profile that is provided by the processor 126 to the nonsinusoidal RF generator 214. For example, a sawtooth-shaped power profile is provided to the nonsinusoidal RF generator 120 and a pulsed power profile is provided to the nonsinusoidal RF generator 214. As another example, a peak magnitude of the power profile provided to the nonsinusoidal RF generator 120 is different than a peak magnitude of the power profile provided to the nonsinusoidal RF generator 214. As yet another example, the power profile provided to the nonsinusoidal RF generator 120 has a different phase than that of the power profile provided to the nonsinusoidal RF generator 214.

[0078] In several embodiments, the power profile that is provided to the nonsinusoidal RF generator 120 is the same as that of the power profile that is provided to the nonsinusoidal RF generator 214.

[0079] The power amplifier 212 receives the nonsinusoidal RF signal 218 and amplifies the nonsinusoidal RF signal 218 to generate an amplified nonsinusoidal RF signal 220. For example, the power amplifier 212 increases a magnitude of power of the nonsinusoidal RF signal 218 to generate the amplified nonsinusoidal RF signal 220.

[0080] In several embodiments, the power amplifier 212 applies a different amount of amplification to the nonsinusoidal RF signal 218 than that applied by the power amplifier 118 (Figure ^{1A}~~1~~) to the nonsinusoidal RF signal 130 (Figure ^{1A}~~1~~). For example, the power amplifier 212 applies an amplification ratio of $x1:1$ to the nonsinusoidal RF signal 218 and the power amplifier 118 applies an amplification ratio of $x2:1$ to the nonsinusoidal RF signal ¹³⁰~~218~~, where $x1$ and $x2$ are real numbers greater than zero. In some embodiments, $x2$ is greater than $x1$ and in other embodiments, $x2$ is less than or equal to $x1$.

[0081] In a number of embodiments, the power amplifier 212 applies the same amount of amplification to the nonsinusoidal RF signal 218 as that applied by the power amplifier 118 to the nonsinusoidal RF signal 130.

[0082] The filter 210 filters the amplified sinusoidal RF signal 220 by using a filtering signal 222 to generate a filtered nonsinusoidal RF signal 224. In various

embodiments, the filtered nonsinusoidal RF signal 224 is a pulsed waveform that has a duty cycle that ranges from 10% to 90%. In some embodiments, the filtered nonsinusoidal RF signal 224 is a pulsed waveform that has a duty cycle that ranges from 1% to 99%. In some embodiments, the duty cycle of the filtered nonsinusoidal RF signal 224 is the same as the duty cycle of the filtering signal 222.

[0083] In some embodiments, the filter 210 applies a different filter to the amplified nonsinusoidal signal 220 than that applied by the filter 116 to the amplified nonsinusoidal signal 132 (Figure 1A). For example, the filter 210 applies a low-pass filter to the amplified nonsinusoidal signal 220 and the filter 116 applies a band-pass filter to the amplified nonsinusoidal signal 132. As another example, the filter 210 applies a notch filter to the amplified nonsinusoidal signal 220 and the filter 116 applies a comb filter to the amplified nonsinusoidal signal 132.

[0084] In a number of embodiments, the filter 210 applies the same filter to the amplified nonsinusoidal signal 220 as that applied by the filter 116 to the amplified nonsinusoidal signal 132.

[0085] The filtered nonsinusoidal RF signal 224 is provided by the filter 210 to the surface antenna 104. Moreover, the sinusoidal RF generator 202 generates a sinusoidal RF signal and provides the sinusoidal RF signal to the ESC ¹⁰⁸ ~~208~~ via the impedance matching circuit 204. In some embodiments, the processor 126 provides a frequency of the sinusoidal RF signal and power of the sinusoidal RF signal to the sinusoidal RF generator 202 and the sinusoidal RF generator 202 generates the sinusoidal RF signal having the power and the frequency.

[0086] In some embodiments, the frequency of operation of the nonsinusoidal RF generator 214 is the same as the frequency of operation of the sinusoidal RF generator 202. For example, the frequency of operation of the nonsinusoidal RF generator 214 ranges between 13 MHz and 14 MHz. As another example, the frequency of operation of the nonsinusoidal RF generator 214 is less than 13 MHz. As another example, the frequency of the nonsinusoidal RF signal 218 is the same as the frequency of the sinusoidal RF signal that is generated by the sinusoidal RF generator 202.

[0087] In several embodiments, the frequency of operation of the nonsinusoidal RF generator 214 is different from the frequency of operation of the sinusoidal RF generator 202.

the nonsinusoidal RF generator 120 to generate the nonsinusoidal RF signal 304 having the power profile. It should be noted that power magnitude as a function of time includes a frequency of the nonsinusoidal RF signal 304. The power amplifier 118 receives the nonsinusoidal RF signal 304 and amplifies the nonsinusoidal RF signal 304 to generate an amplified nonsinusoidal RF signal 306. For example, the power amplifier 118 increases a magnitude of power of the nonsinusoidal RF signal 304 to generate the amplified nonsinusoidal RF signal 306.

[0094] The filter 116 filters the amplified ~~sinusoidal~~ ^{nonsinusoidal} RF signal 306 by using a filtering signal 308 to generate a filtered nonsinusoidal RF signal 310. In various embodiments, the filtered nonsinusoidal RF signal 310 is a pulsed waveform that has a duty cycle that ranges from 10% to 90%. In some embodiments, the filtered nonsinusoidal RF signal 310 is a pulsed waveform that has a duty cycle that ranges from 1% to 99%. The filtered nonsinusoidal RF signal 310 is provided by the filter 116 to the ESC 112. In some embodiments, the duty cycle of the filtered nonsinusoidal RF signal 310 is the same as the duty cycle of the filtering signal 308.

[0095] Moreover, the nonsinusoidal RF generator 214 generates a nonsinusoidal RF signal 312 having a frequency of operation received from the processor 126 and provides the nonsinusoidal RF signal 312 to the power amplifier 212.

[0096] In some embodiments, the processor 126 provides a power profile, e.g., power magnitude as a function of time, etc., to the nonsinusoidal RF generator 214 to generate the nonsinusoidal RF signal 312 having the power profile. It should be noted that power magnitude as a function of time includes a frequency of the nonsinusoidal RF signal 312.

[0097] In some embodiments, the frequency of operation of the nonsinusoidal RF generator 214 is the same as the frequency of operation of the nonsinusoidal RF generator 120. As an example, the frequency of the nonsinusoidal RF signal 304 is the same as the frequency of the nonsinusoidal RF signal 312.

[0098] In several embodiments, the frequency of operation of the nonsinusoidal RF generator 214 is different from the frequency of operation of the nonsinusoidal RF generator 120.

[0099] The power amplifier 212 receives the nonsinusoidal RF signal 312 and amplifies the nonsinusoidal RF signal 312 to generate an amplified nonsinusoidal RF signal

314. For example, the power amplifier 212 increases a magnitude of power of the nonsinusoidal RF signal 312 to generate the amplified nonsinusoidal RF signal 314.

[00100] In several embodiments, the power amplifier 212 applies a different amount of amplification to the nonsinusoidal RF signal 312 than that applied by the power amplifier 118 (Figure 1) to the nonsinusoidal RF signal 304. For example, the power amplifier 212 applies an amplification ratio of 2:1 to the nonsinusoidal RF signal 312 and the power amplifier 118 applies an amplification ratio of 3:1 to the nonsinusoidal RF signal 304.

[00101] In a number of embodiments, the power amplifier 212 applies the same amount of amplification to the nonsinusoidal RF signal 312 as that applied by the power amplifier 118 to the nonsinusoidal RF signal 304.

[00102] The filter 210 filters the amplified ~~sinusoidal~~ ^{nonsinusoidal} RF signal 314 by using a filtering signal 316 to generate a filtered nonsinusoidal RF signal 318. In various embodiments, the filtered nonsinusoidal RF signal 318 is a pulsed waveform that has a duty cycle that ranges from 10% to 90%. In some embodiments, the filtered nonsinusoidal RF signal 318 is a pulsed waveform that has a duty cycle that ranges from 1% to 99%. In some embodiments, the duty cycle of the filtered nonsinusoidal RF signal 318 is the same as the duty cycle of the filtering signal 316.

[00103] In several embodiments, the duty cycle of the filtered nonsinusoidal RF signal 318 is different from the duty cycle of the filtered nonsinusoidal RF signal 310. For example, the duty cycle of the filtered nonsinusoidal RF signal 318 is less than the duty cycle of the filtered nonsinusoidal RF signal 310. As another example, the duty cycle of the filtered nonsinusoidal RF signal 318 is greater than the duty cycle of the filtered nonsinusoidal RF signal 310. In a number of embodiments, the duty cycles of the filtered nonsinusoidal RF signals 310 and 318 are the same.

[00104] In some embodiments, the filter 210 applies a different filter to the amplified nonsinusoidal signal 314 than that applied by the filter 116 to the amplified nonsinusoidal signal 306. For example, the filter 210 applies a high-pass filter to the amplified nonsinusoidal signal 314 and the filter 116 applies a band-pass filter to the amplified nonsinusoidal signal 306. As another example, the filter 210 applies a low-pass filter to the amplified nonsinusoidal signal 314 and the filter 116 applies a comb filter to the amplified nonsinusoidal signal 306.

[00105] In a number of embodiments, the filter 210 applies the same filter to the amplified nonsinusoidal signal 314 as that applied by the filter 116 to the amplified nonsinusoidal signal 306.

[00106] The filtered nonsinusoidal RF signal 318 is provided by the filter 210 to the surface antenna 104 and the filtered nonsinusoidal RF signal 310 is provided by the filter 116 to the ESC 108. When one or more of the process gases are supplied via the gas distribution plate 106 in a space of the plasma chamber 102 between the surface antenna 104 and the ESC 108, and when the filtered nonsinusoidal RF signal 310 is supplied to the ESC 108, and when the filtered nonsinusoidal RF signal 318 is supplied to the surface antenna 104, the one or more process gases are ignited to generate plasma within the plasma chamber 102 and to achieve the ion energy 674 that is linked with a power profile of the recipe 302. The power profile of the recipe 302 is further described below. The plasma is used to process, e.g., etch, sputter, etc., the workpiece 110.

[00107] Figure 2A is a diagram of an embodiment of an inductive coil 350 that is ~~an example of~~ the surface antenna 104 (Figures 1A thru 1C). The inductive coil 350 is coupled to the RF generator 114 at one end of the inductive coil ~~250~~³⁵⁰ and is coupled to a ground connection at an opposite end 354 of the inductive coil 350.

[00108] Figure 2B is a diagram of an embodiment of the inductive coil 350 that is coupled to ground connections at both ends 352 and 354 of the inductive coil 350. The RF generator 114 is coupled the inductive coil 350 at a position 356 that is located between the two ends 352 and 354 of the inductive coil 350.

[00109] Figure 3A is a diagram of an embodiment of a system 400 for filtering a signal to provide a filtered signal to the ESC 108 or to the surface antenna 104. The system 400 includes a nonsinusoidal RF generator 402, a power amplifier 404, and a switch 406.

[00110] The nonsinusoidal RF generator 402 is an example of the nonsinusoidal RF generator 120 (Figures 1A & 1C) and an example of the nonsinusoidal RF generator 214 (Figures 1B & 1C). The nonsinusoidal RF generator 402 is coupled to the power amplifier 404 and the power amplifier 404 is coupled to the switch 406.

[00111] Moreover, the power amplifier 404 is an example of the power amplifier 118 (Figures 1A & 1C) and of the power amplifier 212 (Figures 1B & 1C). The switch 406 is an example of the filter 116 (Figures 1A & 1C) and of the filter 210 (Figures 1B & 1C).

that is measured by the wafer bias sensor 672 and determines the ion energy 674 from the wafer bias in the same manner as that described above with reference to Figure 10A.

[00187] The recipe 216 includes a power profile 704, which is power of the amplified nonsinusoidal signal 220 that is generated by the power amplifier 212 as a function of time to achieve the ion energy 674. The recipe 216 further includes other parameters, e.g., pressure within the plasma chamber 102, temperature within the plasma chamber 102, gap between the surface antenna 104 and the ESC 108, a frequency of operation of the nonsinusoidal RF generator 214.

[00188] Plasma is formed in the plasma chamber 102 using the recipe 216. For example, plasma is formed within the plasma chamber 102 when an amount of pressure is maintained within the space of the plasma chamber 102, when an amount of temperature is maintained within the plasma chamber 102, when an amount of vertical gap between the surface antenna 104 and the ESC 108 is maintained within the plasma chamber, when the amplified nonsinusoidal signal 220 having the power profile 704 is generated, and when the nonsinusoidal RF generator 214 operates at a frequency of operation.

[00189] In several embodiments, the processor 126 retrieves the power profile 704 from the memory device 128 and provides the power profile 704 to the nonsinusoidal RF generator 214 and to the power amplifier 212. Upon receiving the power profile 704, the nonsinusoidal RF generator 214 generates the nonsinusoidal RF signal 218. Moreover, upon receiving the power profile 704 and the nonsinusoidal RF signal 218, the power amplifier 212 generates the amplified nonsinusoidal RF signal 220 having the power profile 704.

[00190] In a number of embodiments, the nonsinusoidal RF generator 214 receives a frequency of operation of the nonsinusoidal RF signal ²¹⁸~~214~~ from the processor 126 and generates the nonsinusoidal RF signal 218 having the frequency.

[00191] The processor 126 associates, e.g., forms a link between, etc., the power profile 704 and the ion energy 674.

[00192] Figure 10C is a block diagram of a calibration plasma system 720 for determining a power profile to achieve ion energy when the filtered nonsinusoidal signal 310 (Figure 1C) is applied to the ESC 108 and when the filtered nonsinusoidal signal 318 (Figure 1C) is applied to the surface antenna 104. During calibration, the amplified nonsinusoidal signal 306 is generated in the same manner as that described above with reference to Figure 1C and is applied to the ESC 108 and the amplified nonsinusoidal signal 314 is generated in

[00202] In various embodiments, a power profile includes any number of power amplitudes to be maintained during a clock cycle. Moreover, in some embodiments in which two nonsinusoidal RF generators are used simultaneously, e.g., the use of the nonsinusoidal RF generators 120 and 214 in the plasma system 300 (Figure 1C), etc., instead of one frequency of operation, the recipe A includes two frequencies of operation, one for the nonsinusoidal RF generator 120 and another for the nonsinusoidal RF generator 214. Also, in these embodiments, instead of one set of the power profiles f1, g1, h1, and i1, the recipe A includes two sets of power profiles, one that includes power amplitudes of the amplified nonsinusoidal signal 306 and another that includes power profiles of the amplified nonsinusoidal signal 314.

[00203] The recipe B indicates that a pressure a2 Torr be maintained within the plasma chamber 102 (Figures 1A thru 1C, Figures 10A thru 10C), that a temperature b2 degrees Fahrenheit be maintained within the plasma chamber 102, and that a frequency of operation of d2 of a nonsinusoidal RF generator, e.g., the nonsinusoidal RF generator 120 (Figure 1A, Figure 10A), the nonsinusoidal RF generator 214 (Figure 1B, Figure 10B), etc., be maintained. Moreover, the recipe B indicates that a gap between the surface antenna 104 and the ESC 108 of e2 nm be maintained, and that a power profile of an amplified nonsinusoidal signal, e.g., the amplified nonsinusoidal signal 132 (Figure 1A), the amplified nonsinusoidal signal 220 (Figure 1B), etc., having power amplitudes f2, g2, h2, and i2 at different times of a clock cycle be maintained.

[00204] In various embodiments, a power profile includes any number of power amplitudes to be maintained during a clock cycle. Moreover, in some embodiments in which two nonsinusoidal RF generators are used simultaneously, e.g., the use of the nonsinusoidal RF generators 120 and 214 in the plasma system 300 (Figure 1C), etc., instead of one frequency of operation, the recipe B includes two frequencies of operation, one for the nonsinusoidal RF generator 120 and another for the nonsinusoidal RF generator 214. Also, in these embodiments, instead of one set of the power profiles f2, g2, h2, and i2, the recipe B includes two sets of power profiles, one that includes power amplitudes of the amplified sinusoidal signal 306 and another that includes power profiles of the amplified sinusoidal signal 314.

[00205] In various embodiments, at least one but not all values of the recipes A and B are same. For example, the value a1 is equal to a2, the value b1 is equal to b2, the value c1 is equal to c2, the value d1 is equal to d2, the value e1 is equal to e2, the value f1 is equal to

7. The system of claim 6, wherein the pulsed waveform has an on cycle and an off cycle, the pulsed waveform having a magnitude of zero during the ~~on~~^{off} cycle and a magnitude greater than zero during the ~~off~~^{on} cycle.

8. A system for controlling ion energy within a plasma chamber, comprising:
a sinusoidal radio frequency (RF) generator for generating a sinusoidal signal;
a chuck coupled to the sinusoidal RF generator for receiving the sinusoidal signal;
a nonsinusoidal radio frequency (RF) generator for generating a nonsinusoidal signal;
a power amplifier coupled to the nonsinusoidal RF generator, the power amplifier for amplifying the nonsinusoidal signal to generate an amplified signal;
a filter coupled to the power amplifier, the filter for filtering the amplified signal using a filtering signal to generate a filtered signal; and
an upper electrode coupled to the filter, the upper electrode facing the chuck, the upper electrode for receiving the filtered signal to facilitate achieving ion energy at the chuck to be between a lower threshold and an upper threshold.

9. The system of claim 8, wherein the upper electrode is a surface inductor or a capacitive plate.

10. The system of claim 8, wherein the nonsinusoidal RF generator includes a driver and a filter, the filter of the nonsinusoidal RF generator for filtering a sinusoidal RF signal that is generated by the driver to generate the nonsinusoidal signal.

11. The system of claim 8, wherein the power amplifier increases a magnitude of the nonsinusoidal signal.

12. The system of claim 8, wherein the lower threshold includes a lower value and the upper threshold includes an upper value, the upper value higher than the lower value.

13. The system of claim 8, wherein the filtered signal is a pulsed waveform, wherein the filtered signal has a same duty cycle as that of the filtering signal.

14. The system of claim 13, wherein the pulsed waveform has an on cycle and an off cycle, the pulsed waveform having a magnitude of zero during the ~~on~~^{off} cycle and a magnitude greater than zero during the ~~off~~^{on} cycle.

15. The system of claim 8, wherein the ion energy is determined based on a wafer bias at the chuck and a peak-to-peak voltage at the chuck.

16. A system for controlling ion energy within a plasma chamber, comprising:
a first nonsinusoidal radio frequency (RF) generator for generating a ~~nonsinusoidal~~^{first nonsinusoidal} signal;

a first power amplifier coupled to the first nonsinusoidal RF generator, the first power amplifier for amplifying the first nonsinusoidal signal to generate a first amplified signal;

a first filter coupled to the first power amplifier, the first filter for filtering the first amplified signal using a first filtering signal to generate a first filtered signal;

an upper electrode coupled to the first filter;

a second nonsinusoidal RF generator for generating a second nonsinusoidal signal;

a second power amplifier coupled to the second nonsinusoidal RF generator, the second power amplifier for amplifying the second nonsinusoidal signal to generate a second amplified signal;

a second filter coupled to the second power amplifier, the second filter for filtering the second amplified signal using a second filtering signal to generate a second filtered signal; and

a chuck coupled to the second filter, the chuck facing the upper electrode, the chuck including a lower electrode, the lower electrode for receiving the second filtered signal to facilitate achieving the ion energy at the chuck to be between ~~a~~^a lower threshold and ~~the~~^{an} upper threshold, the upper electrode for receiving the first filtered signal to facilitate achieving ion energy at the chuck to be between ~~a~~^{the} lower threshold and ~~an~~^{the} upper threshold.

17. The system of claim 16, wherein the first nonsinusoidal RF generator includes a first driver and a first filter, the first filter of the first nonsinusoidal RF generator for filtering a sinusoidal RF signal that is generated by the first driver to generate the first nonsinusoidal signal, wherein the second nonsinusoidal RF generator includes a second driver and a second filter, the second filter of the second nonsinusoidal RF generator for filtering a sinusoidal RF signal that is generated by the second driver to generate the second nonsinusoidal signal.