(19) **United States**
(12) **Patent Application Publication** (10) **Pub. No.: US 2003/0137251 A1**
Mitrovic et al. (43) **Pub. Date: Jul. 24, 2003**

(54) **METHOD AND APPARATUS FOR IMPROVED PLASMA PROCESSING UNIFORMITY**

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(21) Appl. No.: **10/359,557**

(22) Filed: **Feb. 7, 2003**

Related U.S. Application Data

(63) Continuation of application No. PCT/US01/24491, filed on Aug. 6, 2001.

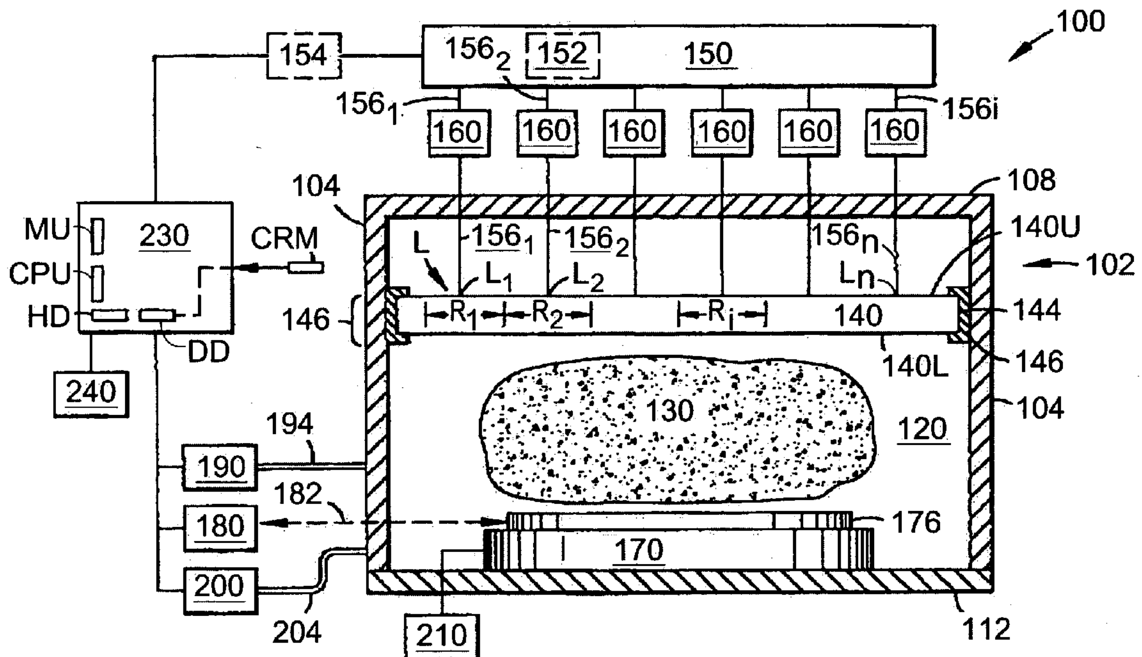
(60) Provisional application No. 60/223,834, filed on Aug. 8, 2000.

Publication Classification

(51) **Int. Cl.**^{7} **H01J 19/80**
(52) **U.S. Cl.** **315/111.21**; 315/39

(57) **ABSTRACT**

A method and apparatus for generating and controlling a plasma **(130)** formed in a capacitively coupled plasma system **(100)** having a plasma electrode **(140)** and a bias electrode in the form of a workpiece support member **(170)**, wherein the plasma electrode is unitary and has multiple regions (R_i) defined by a plurality of RF power feed lines **(156)** and the RF power delivered thereto. The electrode regions may also be defined as electrode segments **(420)** separated by insulators **(426)**. A set of process parameters $A=\{n, \tau_i, \Phi_i, P_i, S; L_i\}$ is defined, herein n is the number of RF feed lines connected to the electrode upper surface at locations L_i, τ_i is the on-time of the RF power for the ith RF feed line, Φ_i is the phase of the ith RF feed line relative to a select one of the other RF feed lines, P_i is the RF power delivered to the electrode through the ith RF feed line at location L_i, and S is the sequencing of RF power to the electrode through the RF feed lines. One or more of these parameters are adjusted so that operation of the plasma system results in a workpiece **(176)** being processed with a desired amount or degree of process uniformity.



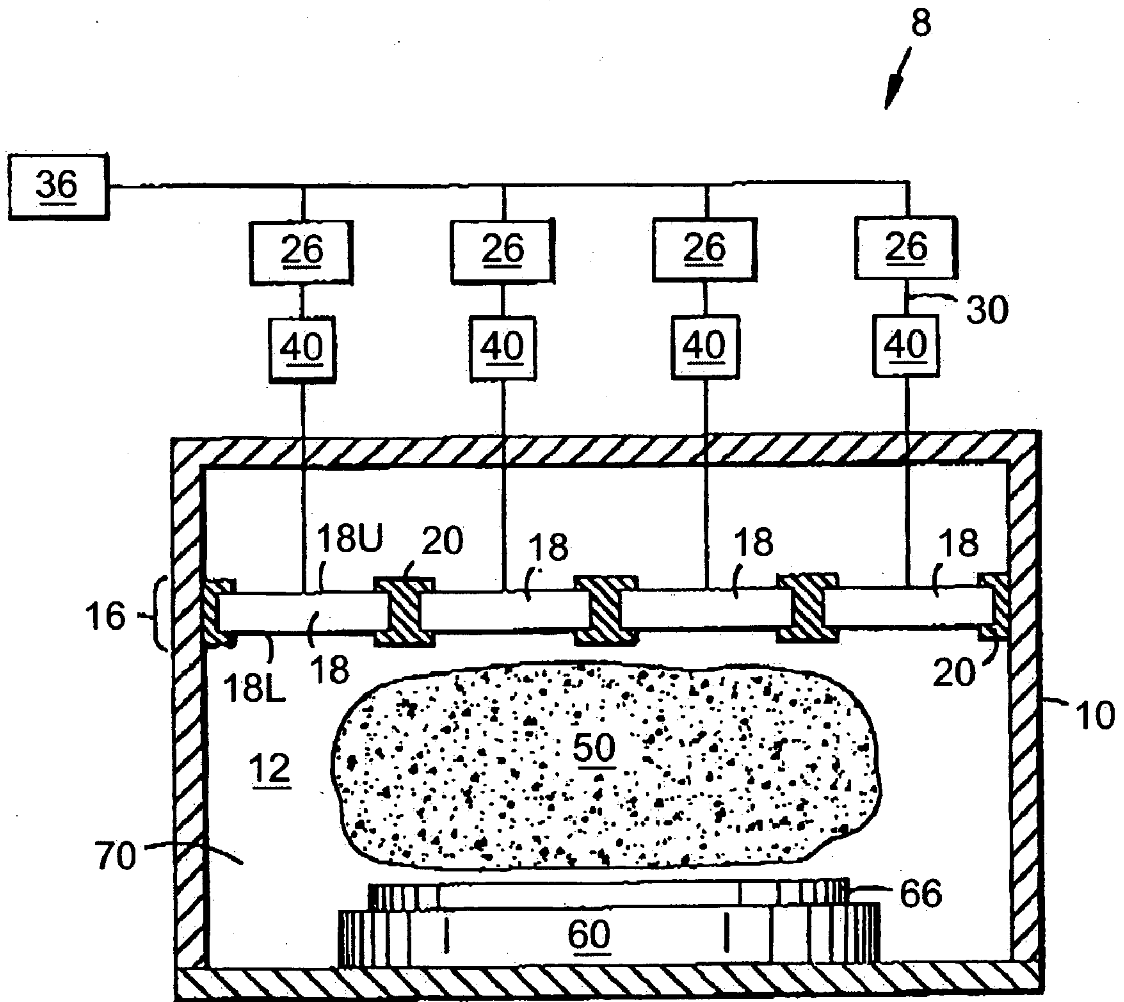


Fig. 1
PRIOR ART

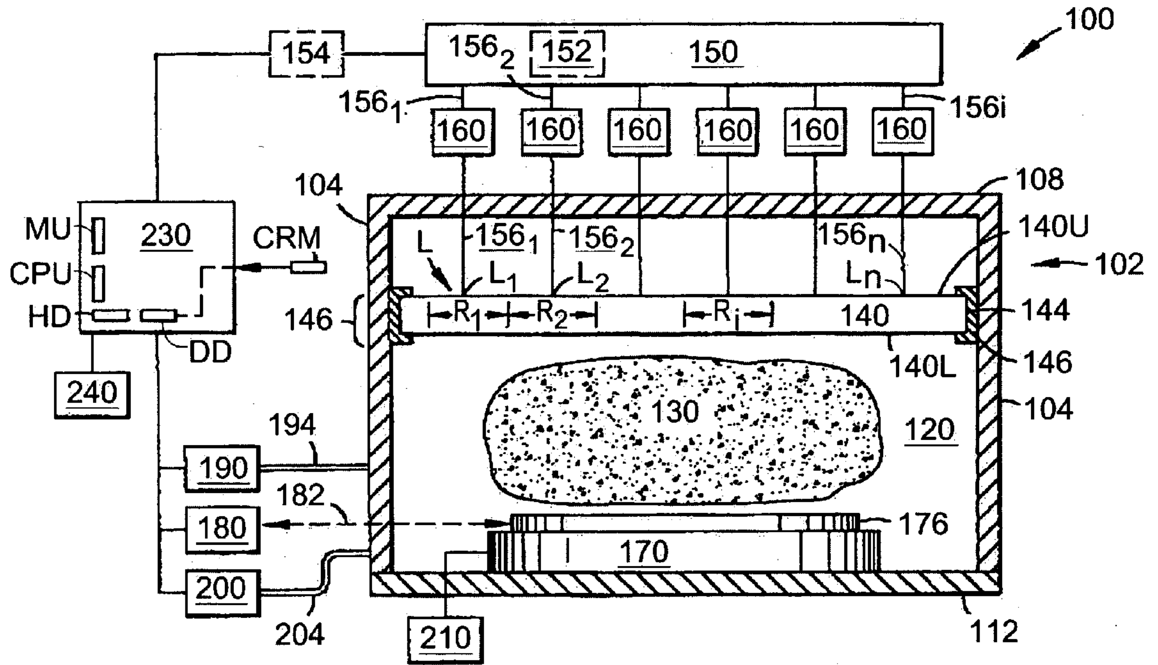


Fig. 2A

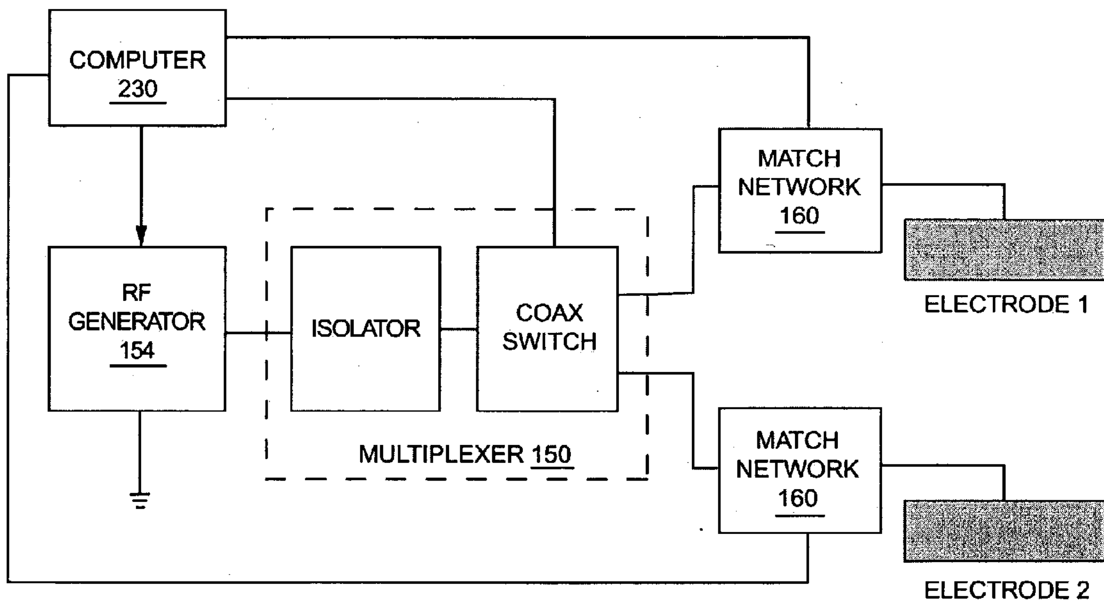


Fig. 2B

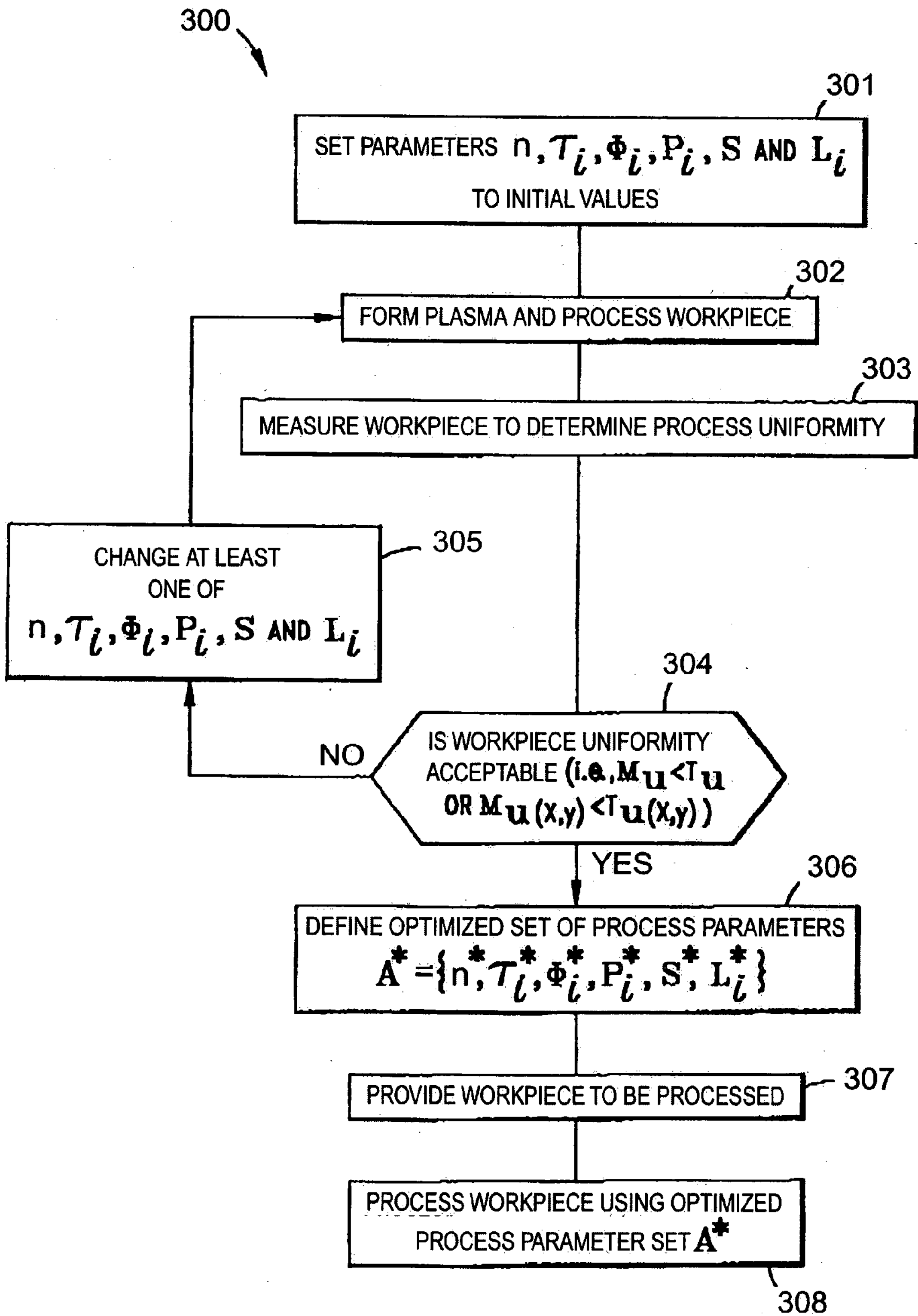


Fig. 3

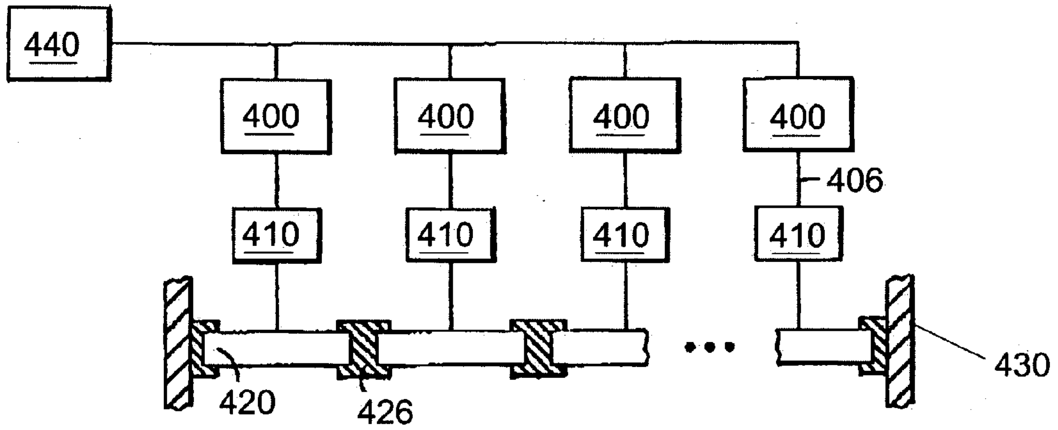


Fig. 4A

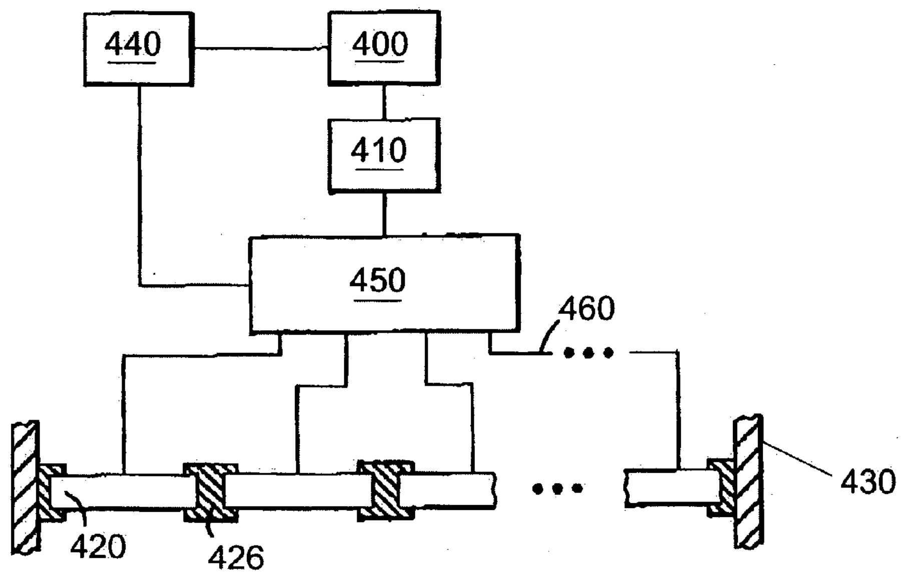


Fig. 4B

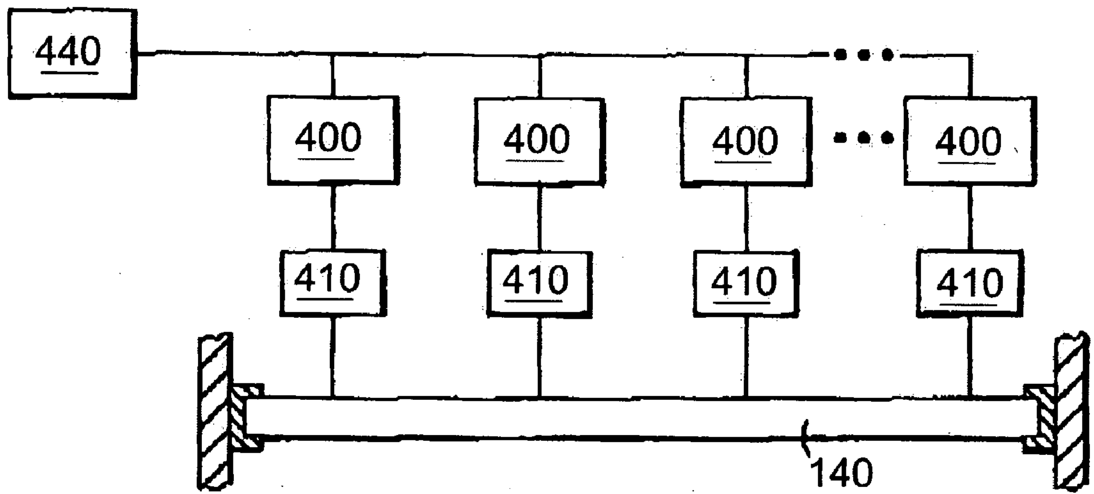


Fig. 4C

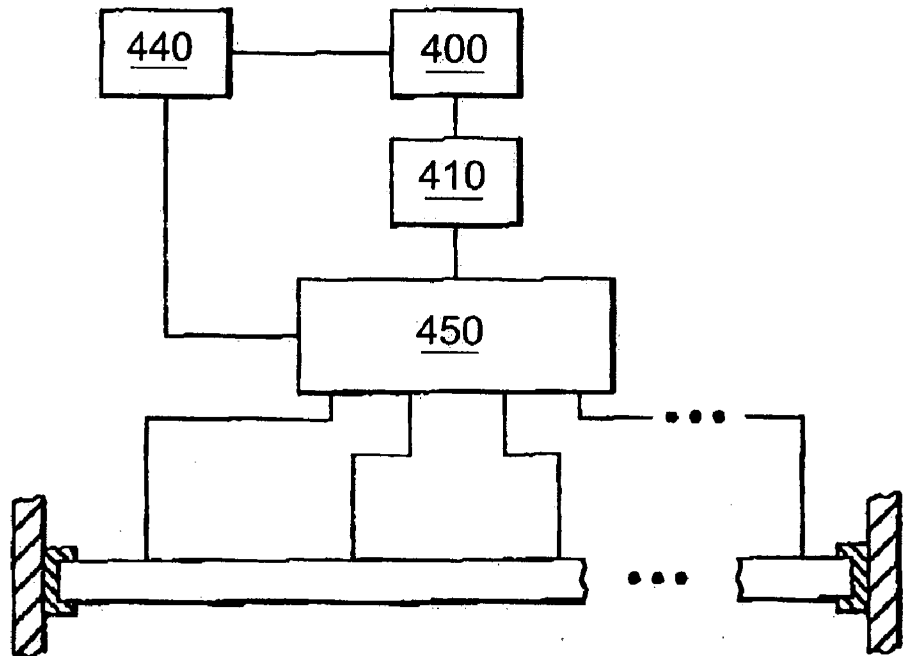


Fig. 4D

METHOD AND APPARATUS FOR IMPROVED PLASMA PROCESSING UNIFORMITY

[0001] This is a continuation of International Application No. PCT/US01/24491, filed on Aug. 6, 2001, and also claims benefit of U.S. application No. 60/223,834, filed Aug. 8, 2000, the contents of both of which are incorporated herein in their entirety by reference.

BACKGROUND OF THE INVENTION

[0002] The present invention pertains to plasma processing of workpieces, and in particular pertains to a method and apparatus for improving the uniformity of plasma processing.

[0003] Ionized gas or "plasma" may be used during processing and fabrication of semiconductor devices, flat panel displays and other products requiring etching or deposition of materials. Plasma may be used to etch or remove material from semiconductor integrated circuit wafers, or to sputter or deposit material onto a semiconducting, conducting or insulating surface. Creating a plasma for use in manufacturing or fabrication processes typically is done by introducing a low-pressure process gas into a chamber surrounding a workpiece such as an integrated circuit (IC) wafer. The atoms or molecules of the low-pressure gas in the chamber are ionized to form plasma by a radio frequency energy (power) source after the gas molecules enter the chamber. The plasma then flows over and interacts with the workpiece. The chamber is used to maintain the low pressures required for plasma formation, to provide a clean environment for processing the semiconductor devices and to serve as a structure for supporting one or more radio frequency energy sources.

[0004] Plasma may be created from a low-pressure process gas by inducing an electron flow that ionizes individual gas atoms or molecules by transfer of kinetic energy through individual electron-gas molecule collisions. Typically, electrons are accelerated in an electric field such as one produced by radio frequency (RF) energy. This RF energy may be low frequency (below 550 KHz), high frequency (e.g., 13.56 MHz), or microwave frequency (e.g., 2.45 GHz).

[0005] The two main types of etching in semiconductor processing are plasma etching and reactive ion etching (RIE). A plasma etching system typically includes a radio frequency energy source and a pair of electrodes. A plasma is generated between the electrodes, and the workpiece (i.e., substrate or wafer) to be processed is arranged parallel to one of the electrodes. The chemical species in the plasma are determined by the source gas(es) used and the desired process to be carried out.

[0006] A problem that has plagued prior art plasma reactor systems is the control of the plasma to obtain uniform etching and deposition. In plasma reactors, the degree of etch or deposition uniformity is determined by the design of the overall system, and in particular by the design of the RF feed transmission and the associated control circuitry.

[0007] In a plasma reactor system, the electrode is connected to a RF power supply. The technological trend in plasma reactor design is to increase the fundamental RF driving frequency of the RF power supply from the traditional value of 13.56 MHz to 60 MHz or higher. Doing so improves process performance, but increases the complexity of reactor design.

[0008] One approach to improving etch and deposition uniformity has been to use a multi-segment electrode. With reference to **FIG. 1**, plasma reactor system **8** comprises reactor chamber **10** having an interior **12**, within which is arranged a segmented electrode **16** having separate thick conducting electrode segments **18** each with an upper surface **18**U and a lower surface **18**L. A silicon slab or "facing" (not shown) may be attached to each of the lower surfaces **18**L of the segmented electrode by suitable attachment means to control contamination due to sputtering of the metal electrode. Electrode segments **18** are separated by an insulator **20** and are powered by corresponding RF power supplies **26** via RF feed lines **30** connected to respective electrode segments. Power control to electrode segments **18** is provided by a main control unit **36**. Match networks **40** arranged between RF power supplies **26** and electrode segments **18** are tuned to provide the best match to the load associated with a plasma **50** formed in interior region **12**, so as to optimize power transfer to the plasma.

[0009] Reactor system **8** includes a workpiece support member **60** opposite segmented electrode **16**, upon which a workpiece **66**, such as a wafer, is supported. The design of segmented electrode **16** is such that lower surfaces **18**L of electrode segments **18** interfaces with a vacuum region **70** in interior region **12**. This puts electrode segments **18** directly in contact with plasma **50** formed in vacuum region **70**, although if silicon facings as mentioned above (not shown) are used, the surfaces of the silicon electrode facings will be directly in contact with plasma **50**. Numerous seals (not shown) are required between insulators **20** and the electrode segments, and between the chamber **10** and insulators **20**, to isolate vacuum region **70**.

[0010] Current plasma reactor systems can perform an etch process with approximately 5% non-uniformity. This level of performance is sufficient to meet near-term needs for state-of-the-art process performance, but will soon be inadequate as the demands on the manufacturing process increase to require, on a routine basis, non-uniformity below 5%.

[0011] In light of the demands on improving process speed, one technological trend in plasma reactor design is to increase the fundamental RF frequency from the traditional value of 13.454 MHz to 60 MHz or higher, as mentioned above. Doing so improves process performance, but increases the complexity of reactor design. A second trend in reactor design is to have multiple electrodes, i.e., electrode segments, such as those discussed above in connection with **FIG. 1**. However, multiple electrodes combined with increased operating frequencies mean that delivering the correct amount of RF power becomes more complicated because of capacitive coupling between the electrode segments and greater sensitivity to parasitic capacitive and inductive elements. This effect is exacerbated by the shorter wavelengths of higher fundamental frequencies. The result is increased difficulty in reducing process non-uniformity.

[0012] In addition, current multi-segmented electrode plasma reactors require a power supply for each electrode. Thus, if there are five electrode segments, there must be five corresponding power supplies (or separate amplifiers). This leads to high cost and increased maintenance requirements and thus high wafer processing costs. This cost and increased maintenance might be worthwhile if there were a

way to improve the performance of such a system to provide a higher degree of etch or deposition uniformity beyond the present limits of existing plasma processing systems.

BRIEF SUMMARY OF THE INVENTION

[0013] The present invention pertains to plasma processing of workpieces, and in particular pertains to a method and apparatus for improving the uniformity of the plasma processing.

[0014] The present invention is a method of and apparatus for generating and controlling a plasma formed in a capacitively coupled plasma system having a plasma electrode and a bias electrode, wherein the plasma electrode has multiple regions defined by RF power feed lines, with the size of each region being dependent on the amount of RF power delivered thereto. The electrode regions can also be defined as electrode segments separated by insulators. The RF power to each electrode region is independently controlled. In particular, the amplitude, phase, frequency, and/or "on-time" during which the RF power is applied to each RF feed line of the electrode can be varied, thereby affecting the spatial distribution of the plasma-exciting electric field and the plasma density (i.e., ion density) of the plasma.

[0015] Accordingly, a first aspect of the invention is an electrode apparatus for use in plasma processing. The apparatus comprises a unitary electrode having an upper surface and a lower surface. A unitary electrode is an electrode, usually planar, for which the entire electrode comprises either a single conductor or a plurality of conductors that are interconnected by means of low resistance ohmic contacts. A silicon facing; i.e., a so-called silicon electrode, can be attached by various attachment means to the lower surface of the unitary electrode in accordance with common practice. An RF multiplexer is electrically connected to a plurality of locations on the electrode upper surface via a corresponding plurality of RF feed lines. The unitary electrode has a plurality of electrode regions corresponding to the plurality of RF feed lines. These electrode regions are akin to electrode segments of a segmented electrode, differing therefrom in that the electrode regions of a unitary electrode are not separated by insulators. The apparatus can preferably include a plurality of match networks arranged one in each RF feed line in said plurality of RF feed lines. The apparatus can also preferably include a control system electrically connected to the RF multiplexer, for controlling the operation of said RF multiplexer when performing RF multiplexing.

[0016] A second aspect of the present invention is a plasma reactor system for processing a workpiece in a manner that achieves a high degree of process uniformity. The system comprises a plasma chamber having sidewalls, an upper surface and a lower surface defining an interior region capable of supporting plasma. A unitary electrode having an upper surface is arranged within the interior region adjacent the upper wall. A RF multiplexer is electrically connected to a plurality of locations on the upper surface of the unitary electrode via a corresponding plurality of RF feed lines. The electrode includes a plurality of electrode regions corresponding to the plurality of RF feed lines. Also included in the interior region adjacent the lower wall is a workpiece support member for supporting the workpiece.

[0017] A third aspect of the present invention is a method of determining a set of optimum plasma process parameters $A^*=\{n^*, \tau_i^*, \Phi^{i*}, P_i^*, S^*; L_i\}$ for plasma processing a workpiece with a high degree of uniformity. The method is carried out in a plasma reactor chamber having an electrode with an upper surface as part of a plasma reactor system. The parameters are defined as follows: n is the number of RF feed lines connected to the electrode upper surface at locations L_i, τ_i is the on-time of the RF power for the ith RF feed line, Φ^i is the phase of the ith RF feed line relative to a selected one of the other RF feed lines, P_i is the RF power delivered to the electrode at location L_i through the ith RF feed line, and S is the sequencing of RF power to the electrode through the RF feed lines. The method comprises a first step of setting initial values for process parameters n, τ_i, Φ_i, P_i, and S, and then a second step of processing one or more workpieces while varying one or more of said process parameters to determine the optimized set of process parameters $A^*=\{n^*, \tau^{i*}, \Phi^{i*}, P_i^*, S^*\}$ that achieve a process non-uniformity less than the predetermined standard. The second step includes the steps of forming a first plasma within the reactor chamber having characteristics corresponding to the initial process parameters and processing a first workpiece for a predetermined process time, measuring the workpiece process uniformity, and comparing the workpiece process uniformity to a predetermined standard. If the workpiece process non-uniformity is greater than the predetermined standard, then at least one of the process parameters is changed and the above-steps repeated (using either the first workpiece or a different workpiece) until the workpiece process non-uniformity is less than the predetermined standard.

[0018] A fourth aspect of the invention involves processing a workpiece using the optimized process parameters deduced as described above in connection with the third aspect of the invention.

[0019] A fifth aspect of the invention is the method of the first aspect of the invention, but carried out to achieve a desired degree of process uniformity. Such a method might be performed where there is a need to purposely provide a certain amount of process non-uniformity to counter other process effects.

BRIEF DESCRIPTION OF THE SEVERAL VIEWS OF THE DRAWING

[0020] **FIG. 1** is a schematic cross-sectional diagram of a prior art plasma reactor system having a segmented electrode comprising a plurality of electrode segments with corresponding RF power supplies connected thereto;

[0021] **FIG. 2A** is a schematic cross-sectional diagram of the plasma reactor system of the present invention having a unitary electrode with multiple RF feed lines connected at one end to various locations on the unitary electrode upper surface, and connected at the opposite ends to a RF power multiplexer;

[0022] **FIG. 2B** is a block diagram of an embodiment of one component of the system of **FIG. 2A**;

[0023] **FIG. 3** is a flow diagram of the method according to the present invention of optimizing the process parameters of the plasma reactor system of **FIG. 2**;

[0024] **FIG. 4A** is a schematic diagram of a first alternate embodiment for the RF power sources and electrode of the

present invention, wherein multiple RF power supplies feed power through multiple match networks to electrode segments of a multi-segment electrode;

[0025] **FIG. 4B** is a schematic diagram of a second alternate embodiment for the RF power sources and electrode of the present invention, wherein a single RF power supply feeds power through a match network and a multiplexer distributing power to electrode segments in a multi-segment electrode;

[0026] **FIG. 4C** is a schematic diagram of the first alternate embodiment for the RF power sources and electrode of the present invention, wherein multiple RF power supplies feed power through multiple match networks to a unitary electrode; and

[0027] **FIG. 4D** is a schematic diagram of the second alternate embodiment for the RF power sources and electrode of the present invention, wherein a single RF power supply feeds power through a match network and a multiplexer distributing power to electrode regions R_i of a unitary electrode.

DETAILED DESCRIPTION OF THE INVENTION

[0028] The present invention pertains to plasma processing of workpieces, and in particular pertains to a method and apparatus for improving the uniformity of the plasma processing.

[0029] With reference to **FIG. 2**A, plasma reactor system **100** comprises reactor chamber **102** with sidewalls **104**, an upper wall **108** and a lower wall **112** defining an interior region **120** capable of supporting plasma **130**. Arranged within interior region **120** near upper wall **108** is a unitary electrode **140** having an upper surface **140U** and a lower surface **140**L and a periphery **144**. Electrode **140** is referred to as the "plasma electrode". Insulators **146** are arranged between electrode periphery **144** and sidewalls **104** to electrically isolate electrode **140** from chamber **102**. System **100** further includes a RF power multiplexer **150**. A RF power supply **152** is included in RF multiplexer **150**. Alternatively, an external RF power supply (as illustrated by RF power supply **154**) is provided.

[0030] **FIG. 2B** shows an exemplary layout of a multiplexer **150** acting to distribute RF power from a single RF generator **154** sequentially to a plurality of electrodes or electrode regions. Although only two electrodes are illustrated for the sake of simplicity, it will be understood that any number of electrodes can be supplied. In **FIG. 2B** a central computer, or controller, **230** communicates with RF power generator **154**, multiplexer **150** and one or more match networks **160**. Multiplexer **150** is composed of an isolator and a coax switch. The isolator can be a commercially available product of the type distributed by HD Communications Corporation (1 Comac Loop, Ronkonkoma, N.Y. 11779) who specializes in RF, microwave, fiber optic and wireless communications products. In particular, that company distributes and custom builds UHF, VHF, high power circulators and isolators. For instance, devices in the frequency ranges of (VHF) 66-88, 144-225 MHz and (FM) 88-108 MHz are currently available. The coax switch can be a commercially available product distributed by Texas Towers, in particular the Ameritron RCS-8V. The specifications for the Ameritron RCS-8V are as follows: a frequency range of 0.5 to 450 MHz, power handling of 5000 W at 30 MHz, power handling of 1000 W at 150 MHz, <0.05 dB insertion loss and 50 Ω impedance. Generator **154**, match networks **160** and the coax switch of multiplexer **150** are all connected to be controlled by computer **230** to distribute power to the various electrodes in any desired pattern.

[0031] Reverting to **FIG. 2**A, system **100** further includes multiple (n) RF feed lines **156** (e.g., 156_i, where i=**1** to n) connected to multiplexer **150** and that pass through tipper wall **108** and connect at their opposite ends to different locations L_i (e.g., $L_1, L_2, \ldots L_n$) on electrode upper surface **140**U. RF power multiplexer **150** is a device that directs RF power to one or more of the RF feed lines **156** at a given time. The locations L_i of RF feed lines **156** define corresponding electrode regions R_i (e.g., $R_1, R_2, \ldots R_n$) to which RF power is provided. The sizes of regions R_i depend on the amount of RF power P_i provided, relative to the amount of power provided to adjacent regions but typically each of these regions extends over an area of the order of the total electrode area divided by n. For a segmented electrode, when only a single electrode segment is powered, it is known that the highest process rate (etch or deposition rate) on a wafer occurs directly under that powered segment. Although a similar result occurs with a unitary electrode when a RF feed with its L_i axially located is the only powered RF feed, when a RF feed with its L_i located off-axis is the only powered RF feed, the highest process rate on a wafer occurs at a location diametrically opposite to that L_i.

[0032] System **100** also preferably includes match networks **160** arranged in RF feed lines **156** between RF multiplexer **150** and electrode **140**. Match networks **160** are tuned to provide the best match to the load presented by plasma **130** formed within interior region **120** so as to optimize power transfer to the plasma.

[0033] Reactor system **100** further includes a workpiece support member **170** arranged adjacent lower wall **112** opposite segmented electrode **140**, capable of supporting a workpiece **176**, such as a wafer, to be processed (e.g., etched or coated) by means of plasma **130**.

[0034] System **100** also includes a workpiece handling system **180** in operative communication with plasma chamber **102** (see dashed line **182**), for placing workpieces **176** onto and removing workpieces **176** from workpiece support member **170**. Also included is a gas supply system **190** in pneumatic communication with chamber **102** via a gas supply line **194** for supplying gas to chamber interior **120** to purge the chamber and to create plasma **130**. The particular gases included in gas supply system **190** depend on the application. However, for plasma etching applications, gas supply system **190** preferably includes such gases as chlorine, hydrogen-bromide, octafluorocyclobutane, and various other fluorocarbon compounds, etc. For chemical vapor deposition applications, gas supply system **190** preferably includes silane, ammonia, tungsten-tetrachloride, titanium-tetrachloride, and the like.

[0035] Further included in system **100** is a vacuum system **200** in pneumatic communication with chamber **102** via a vacuum line **204**. Also included in system **100** is a workpiece support power supply **210** electrically connected to workpiece support member **170**, for electrically biasing the

workpiece support member. This electrical connection allows workpiece support member **170** to serve as a lower electrode, also referred to as the "bias electrode".

[**0036**] System **100** also includes a main control system **230**, which is in electronic communication with and controls and coordinates the operation of workpiece handling system **180**, gas supply system **190**, vacuum system **200**, workpiece support power supply **210**, and RF power multiplexer **150** through electrical signals. Main control system **230** thus controls the operation of system **100** and the plasma processing of workpieces **176** in the system, as described below.

[**0037**] In a preferred embodiment, main control system **230** is a computer with a memory unit MU having both random-access memory (RAM) and read-only memory (ROM), a central processing unit CPU with a microprocessor (e.g., a PENTIUM™ processor from Intel Corporation), and a hard disk HD, all electrically connected. Hard disk HD serves as a secondary computer-readable storage medium, and may be, for example, a hard disk drive for storing information corresponding to instructions for control system **230** to carry out the present invention, as described below. Control system **230** also preferably includes a disk drive DD, electrically connected to hard disk HD, memory unit MU and central processing unit CPU, wherein the disk drive is capable of accepting and reading (and even writing to) a computer-readable medium CRM, such as a floppy disk or compact disk (CD), on which is stored information corresponding to instructions for control system **230** to carry out the present invention. It is also preferable that control system **230** has data acquisition and control capability. A suitable control system **230** is a computer, such as a DELL PRECISION WORKSTATION **610**™, available from Dell Corporation, Dallas, Tex.

[**0038**] System **100** also includes a database **240** electrically connected to (or alternatively, integral to) control system **230** for storing data pertaining to the plasma processing of workpiece **176**, and for also including predetermined sets of instructions (e.g., computer software) for operating system **100** via control system **230** to process the workpieces.

[**0039**] Method of Operation

[**0040**] The operation of system **100** involves setting numerous process-related parameters that can be modified in optimizing RF power delivery to electrode **140** in a manner that allows the etch or deposition rate to be controlled to obtain a high degree of etch or deposition uniformity (i.e., non-uniformity less than 5%).

[**0041**] These process parameters are the number n of RF feed lines **156** providing power to electrode **140**, the power on-time τ_i for the ith RF feed line (i=1 to n), the phasing Φ_i of the ith RF feed line or combinations of RF feed lines relative to a select one of the RF feed lines, the amount of power P_i delivered to the ith RF feed line, and the sequence S of power P_i delivered to the electrode via each RF feed line and hence to each electrode section R_i. An additional parameter, which is typically fixed but in certain cases can be varied, is the location L_i (L_1, L_2, . . . L_n) at which each of RF feed lines **156** is attached to upper surface **140**U of electrode **140**. These process parameters form a process parameter set $A=\{n, \tau_i, \Phi_i, P_i, S; L_i\}$. Any of the parameters in set A can be combined and varied independently or in concert to achieve the desired workpiece uniformity requirements. These parameters can also be utilized to achieve differential workpiece processing when desired. In either case, the parameter set A that contains an optimized set of parameters is $A^*=\{n^*, \tau_i^*, \Phi_i^*, P_i\ S^*; L_i^*\}$.

[**0042**] The optimum parameter set A* can be achieved empirically using the method comprising the following steps. With reference to the flow diagram **300** of **FIG. 3**, once a workpiece is loaded onto workpiece support member **170**, the first step **301** is setting the parameters n, τ_i, Φ_i, P_i, S, and L_i to initial values. As mentioned above, L_i is typically fixed, but could be varied if the need arises, i.e., if varying the other process parameters does not result in an acceptable process uniformity. These initial values can be decided upon based on data from previously run experiments stored in database **240** or through the assistance of computer modeling. The second step **302** is forming plasma **130** within interior region **120** based on the initial parameter values set in step **301** and processing workpiece **176** with the plasma. Plasma **130** will have time-varying characteristics (e.g., plasma density, energy, etc.) corresponding to the initial values of the process parameters. The plasma characteristics (i.e. plasma density, energy, etc.) will vary in time in that, in particular, their spatial distributions will vary in time throughout the process run due to the RF power and/or other process parameter sequencing through the process run. For instance, a first electrode or electrode region is initially powered for a short time and corresponding to this condition there is a particular spatial distribution of the plasma properties. This short period of time is followed by a second short period of time during which a second electrode or electrode region is powered with a different corresponding distribution of plasma properties. Each of these short steps adds to form the entire process run.

[**0043**] In second step **302**, workpiece **176** is processed with plasma **130** for a process time T_P. During this time, RF multiplexer **150**, under the direction of controller **230**, delivers an amount of RF power Pi to each of the n RF feed lines **156***i* for an "on-time",$\tau_i \ll \tau_P$. This process is referred to herein as "RF power multiplexing." Moreover, the sequencing S and phasing Φ_i of the n RF feed lines is also varied. The sequencing S can be such that only one location L_i at a time is powered, or multiple locations L_i at one time are powered.

[**0044**] Thus, the etch or deposition distribution for the entire process time τ_P can be considered as a linear superposition or a non-linear combination of the etch distributions achieved by applying RF power P_i to each RF feed line **156** based on the initial set of process parameters A. Here, the various parameters, such as the on-time τ_i can be different or the same for each RF feed line **156**$_i$. Further, the amount of RF power P_i delivered can the same for all RF feed lines **156**$_i$ as well.

[**0045**] With continuing reference to flow chart **300** of **FIG. 3**, the next step **303** is measuring the workpiece etch or deposition (i.e., process) uniformity. This is preferably accomplished using well-known optical interferometric techniques. The workpiece uniformity measurement is based on the greatest etch depth/deposition thickness minus the smallest etch depth/deposition thickness divided by two times the mean etch depth/deposition thickness of a large number of sites on the workpiece surface. For a wafer with

a diameter of about 20 centimeters, a reasonable number of measurement sites is approximately 50 to 100. This results in a quantitative workpiece uniformity value M_U.

[0046] The next step **304** is assessing whether or not the workpiece uniformity measurement M_U is acceptable, i.e., less than a certain predetermined standard (e.g., threshold) T_U. It can be the case that a certain degree of non-uniformity is sought to counter other processing effects, such as thin-film thickness variations across the surface of the workpiece. Such variations can be accounted for by measuring the spatial variation in uniformity as a function $M_U(x,y)$ and comparing it to a predetermined standard represented by a spatially dependent function T(x,y) that corresponds to the non-uniformity profile sought. Here, it is assumed that the x-y plane lies in the plane of the workpiece surface being processed.

[0047] If the result in step **304** is that the workpiece uniformity is not acceptable (i.e., the non-uniformity is greater than a predetermined standard), then in the next step **305**, based on the results of step **304**, at least one of the initial process parameters n, τ_i, P_i, S and L_i is changed in the effort to converge to the optimum set of process parameters, $A^*=\{n^*, \tau_i^*, \Phi_i^*, P_i^*, S^*; L_i^*\}$. Changing at least one of the process parameters results in plasma **130** that has time-varying characteristics different from the first-formed plasma **130**. In this sense, plasma **130** represents first, second, third, etc. plasmas similar to but different from one another that may need to be formed in the process of deducing the optimum set of process parameters. As mentioned above, one or more of the process parameters in set A can be changed with the assistance of a computer program or algorithm that models the plasma etch or deposition process.

[0048] One approach to finding the optimum set of parameters A* is through the use of a linear superposition or a non-linear combination of etch or deposition rates based on each electrode region R_i For a linear superposition, this can be stated as:

$$PR(x,y)=(1/T_P)\Sigma\tau_i W_i[PR_i(x,y)], \quad \text{Eq. 1}$$

[0049] where PR(x,y) is the overall process rate, $PR_i(x,y)$ is the process rate for each electrode region R_i, T_P is the total process time (i.e., the sum of the τ_i), and W_i is a weighting coefficient. The summation is performed by summing from 1 to n. The weighting coefficient W_i is a function of at least one of the above-defined process parameters. For a linear optimization, W_i will typically be in the range of 0.9 to 1.1. Here, the weighting coefficients W_i may be determined empirically based on the measurements made in step **303** by varying one or more of the parameter values to arrive at the required weighting coefficients W_i. Other more sophisticated computer models of the plasma etch process can also be used to assist in converging to the optimum process parameter set A*. Also, it will be apparent to one skilled in the art that non-linear equations can also be formed and solved in the manner similar to Eq. 1 to find the set of optimum parameters A*.

[0050] It should be noted here that though there can be a total of n RF feed lines **156** connected to upper surface **140U**, fewer than all n RF feed lines may be activated. Here, it is assumed that n is the number of RF feed lines **156**$_i$ chosen to be activated. This number can be less than the total number of feed lines connected to upper surface **140U** of electrode **140** because optimization of the process parameters can require that a certain group of the n RF feed lines not be activated.

[0051] Steps **302** to **305** are repeated until the measured workpiece uniformity M_U is acceptable, thereby defining the optimum process parameter set A*. Once the iteration of steps **301-305** is completed, then in step **306** the optimum process parameter set A* is defined and recorded in database **240** and/or in control system **230** in memory unit MU. In the next step **307**, a workpiece **176**, such as a semiconductor wafer, is provided by placing the workpiece onto workpiece support member **170** via workpiece handling system **180**. Then, in the next step **308**, main control system **230** controls the formation of an "optimized" version of plasma **130** and controls the processing of workpiece **176** provided in step **307** according to the optimum set of process parameters A* established in step **306** and recorded in database **240** and/or control system **230**. Step **308** is carried out for one or more workpieces **176**. If workpiece **176** needs to be processed with a new plasma process step requiring plasma different from a particular form of plasma **130**, then the steps of flow diagram **300** are repeated for the new plasma process.

[0052] By way of example, n can be five, but might also range between two and ten. A typical process time requires on the order of 60 seconds. If only one RF feed is excited at any given time, then if four sequences S occur with five RF feeds, each sequence S will last for 15 sec. If all of the τ_i are equal, each τ_i will be three seconds. If the τ_i are too short, the demands on the RF matching network(s) can be too great; i.e., steady-state conditions may not be attained during the time τ_i.

[0053] With five RF feeds, one RF feed can be located on the axis of symmetry, with the other four located ninety degrees apart centered on a circle with a diameter approximately equal to ⅔ the wafer diameter. The parameter Φ_i is meaningful only if two or more RF feeds are powered simultaneously. The value for P_i can be nearly equal, but need not be so. To provide high process throughput, it is preferable that the value for Pi should be about the same as the power that would be delivered via a single feed to a conventional electrode.

[0054] Alternate Embodiments

[0055] The present invention, as described above, is a method and apparatus for delivering power at different locations to a unitary electrode. The process parameter optimization and operation method described above can also be applied to a number of alternate structural embodiments as shown in FIGS. 4A-D, below, including a multi-segment electrode having a plurality of electrode segments.

[0056] With reference to **FIG. 4A**, multiple RF power supplies **400** feed power through corresponding multiple RF feed lines **406** and multiple match networks **410** to corresponding electrode segments **420** in a multi-segment electrode. Electrode segments **420** are separated by insulators **426**. In this first alternative embodiment, the number of power supplies, match networks, and electrode segments can be two or greater. A control system **440** similar if not identical to control system **230** is programmed to control the operation of RF power supplies **400** so that they are multiplexed in a manner that replicates the RF power multiplexing operation of RF multiplexer **150** of apparatus **100**.

[**0057**] With reference now to **FIG. 4B, a** single RF power supply **400** feeds power through a single match network **410** and a multiplexer **450** distributes power to electrode segments **420** of the multi-segment electrode via multiple RF feed lines **460**. The number of electrode segments **420** can be two or greater. As described above earlier in connection with system **100**, control system **440**, similar if not identical to control system **230**, controls the operation of multiplexer **450** during the operation of system **100**. In the system shown in **FIG. 4**B, match network **410** may need to be to programmed to adjust itself each time multiplexer **450** switches.

[**0058**] With reference now to **FIG. 4**C, multiple RF power supplies **400** feed power through multiple match networks **410** to a unitary electrode **140**, and control system **440**, similar if not identical to control system **230**, is programmed to control the operation of RF power supplies **400** so that they are multiplexed in a manner that replicates the RF power multiplexing operation of RF multiplexer **150** of apparatus **100**.

[**0059**] With reference now to **FIG. 4**D, there is shown a system essentially the same as that described above in connection with system **100**, except that a single adjustable match network **410** is used instead of a plurality of match networks. In the system of **FIG. 4D, a** single RF power supply **400** feeds power through match network **410** and a multiplexer **450** that distributes power to electrode regions R_i of a unitary electrode.

[**0060**] In alternate embodiments, the embodiments of **FIGS. 4A and 4B** are extended to the use coil antennas wherein an electrode **420** can be a RF antenna.

[**0061**] The many features and advantages of the present invention are apparent from the detailed specification and thus it is intended by the appended claims to cover all such features and advantages of the described method that follow in the true spirit and scope of the invention. Further, since numerous modifications and changes will readily occur to those of ordinary skill in the art, it is not desired to limit the invention to the exact construction and operation illustrated and described. Moreover, the methods and apparatus of the present invention, like related apparatus and methods used in the semiconductor arts that are complex in nature, are often best practiced by empirically determining the appropriate values of the operating process parameters, or by conducting computer simulations to arrive at the optimum process parameters for a given application. Accordingly, all suitable modifications and equivalents should be considered as falling within the spirit and scope of the invention.

What is claimed is:

1. An electrode apparatus for use in plasma processing, comprising:

a) a unitary electrode;

b) a RF power supply; and

c) a RF multiplexer electrically connected to said RF power supply and to a plurality of locations on said unitary electrode via a corresponding plurality of RF feed lines thereby establishing a plurality of electrode regions corresponding to said plurality of RF feed lines.

2. An apparatus according to claim 1, further comprising a plurality of match networks arranged one in each of said plurality of RF feed lines.

3. An apparatus according to claim 2, further including a control system electrically connected for controlling the operation of said RF power supply and said RF multiplexer.

4. A plasma reactor system for processing a workpiece, comprising:

a) a plasma chamber having sidewalls, an upper wall and a lower wall defining an interior region capable of supporting a plasma;

b) a unitary electrode having a plurality of electrode regions, arranged within said interior region adjacent said upper wall;

c) a RF multiplexer electrically connected to the plurality of electrode regions of said unitary electrode via a corresponding plurality of RF feed lines;

d) corresponding to said plurality of RF feed lines; and

e) a workpiece support member, arranged in the interior region adjacent said lower wall, for supporting the workpiece.

5. A system according to claim 4, further comprising:

f) a control system electrically connected to said RF multiplexer, for controlling the operation of said RF multiplexer when processing the workpiece.

6. A system according to claim 5, further comprising:

g) a plurality of match networks each arranged one in a respective one of said plurality of RF feed lines.

7. A system according to claim 6, further comprising:

h) a gas supply system in pneumatic communication with said chamber interior region, for supplying gas to said chamber interior region.

8. A system according to claim 7, further comprising:

i) a workpiece support member RF power supply electrically connected to said workpiece support member, for electrically biasing said workpiece support member.

9. A system according to claim 8, further comprising:

j) a vacuum system pneumatically connected to said chamber interior region.

10. A system according to claim 9, further comprising:

k) a workpiece handling system in operative communication with said workpiece support member, for providing the workpiece to the workpiece support member.

11. A system according to claim 5, further including a database electrically connected to said control system.

12. A method of determining a set of optimum plasma process parameters $A^*=\{n^*, \tau_i^*, \Phi_i^*, P_i^*, S^*; L_i^*\}$ for plasma processing, with a high degree of uniformity, a workpiece in a plasma reactor chamber having an electrode with an upper surface as part of a plasma reactor system, wherein n is the number of RF feed lines connected to the electrode upper surface at locations L_i, t_i is the on-time of the RF power for the ith RF feed line, Φ_i is the phase of the ith RF feed line relative to a select one of the other RF feed lines, Pi is the RF power delivered to the electrode to location L_i through the ith RF feed line, and S is the sequencing of RF power to the electrode through the RF feed lines, the method comprising the steps of:

a) setting initial values for process parameters n, τ_i, Φ_i, P_i, and S; and

b) processing one or more workpieces while varying one or more of said process parameters to determine the optimized set of process parameters $A^*=\{n^*, \tau_i^*, \Phi_i^*, P_i^*, S^*\}$ that achieve a process non-uniformity less than a predetermined standard.

13. A method according to claim 12, wherein said step b) includes the steps of:

i) forming a first plasma within the reactor chamber having characteristics corresponding to said process parameters and processing a first workpiece for a predetermined process time;

ii) measuring the workpiece process uniformity; and

iii) comparing the workpiece process uniformity to a predetermined standard.

14. A method according to claim 13, wherein said step b) further includes the step of:

iv) reducing the workpiece process non-uniformity by changing at least one of said process parameters and repeating said steps i) through iii) using one of said first workpiece and a workpiece other than said first workpiece, until the workpiece process non-uniformity is less than said predetermined standard.

15. A method according to claim 12, wherein in said steps a) and b), the locations L_i of the RF feed lines are parameters in the set A of process parameters that can be varied.

16. A method according to claim 12, wherein the initial process parameter values are determined with the assistance of computer modeling.

17. A method according to claim 12, wherein said step b) includes use of a linear processing model as a basis for varying at least one of the process parameters.

18. A method according to claim 12, wherein said step b) includes use of a nonlinear processing model as a basis for varying at least one of the process parameters.

19. A method according to claim 12, wherein said step b) includes providing RF power P_i to a plurality of electrode segments in a multi-segment electrode by multiplexing RF power via RF power multiplexing.

20. A method according to claim 19, wherein said RF power multiplexing is accomplished by programming a control system electrically connected to a plurality of RF power supplies and electronically controlling the activation of the RF power supplies.

21. A method according to claim 12, wherein said step b) involves providing RF power P_i to a unitary electrode via RF power multiplexing.

22. A method of processing a workpiece to be processed according to claim 12, further including the steps, after said step b), of:

c) providing the workpiece to be processed in the reactor chamber;

d) forming an optimized plasma with the process chamber using the set of optimized process parameters determined in said step b); and

e) processing the workpiece to be processed with the optimized plasma.

23. A method of determining a set of optimum plasma process parameters $A^*=\{n^*, \tau_i^*, \Phi_i^*, P_i^*, S^*; L_i^*\}$ for plasma processing, with a desired degree of uniformity, a workpiece in a plasma reactor chamber having an electrode with an upper surface as part of a plasma reactor system, wherein n is the number of RF feed lines connected to the electrode upper surface at locations L_i, τ_i is the on-time of the RF power for the ith RF feed line, τ_i is the phase of the ith RF feed line relative to a select one of the other RF feed lines, P_i is the RF power delivered to the electrode to location L_i through the i_{th} RF feed line, and S is the sequencing of RF power to the electrode through the RF feed lines, the method comprising the steps of:

a) setting initial values for process parameters n, τ_i, Φ_i, P_i, and S; and

b) processing one or more workpieces while varying one or more of said process parameters to determine the optimized set of process parameters $A^*=\{n^*, \tau_i^*, \Phi_i^*, P_i, S\}$ that achieve a desired process uniformity.

24. A method according to claim 23, wherein said step b) includes the steps of:

i) forming a first plasma within the reactor chamber having characteristics corresponding to said process parameters and processing a first workpiece for a predetermined process time;

ii) measuring the workpiece process uniformity; and

iii) comparing the workpiece process uniformity to a predetermined standard.

25. A method according to claim 23, wherein said step b) further includes the step of:

iv) reducing the workpiece process non-uniformity by changing at least one of said process parameters and repeating said steps i) through iii) using one of said first workpiece and a workpiece other than said first workpiece, until the workpiece process non-uniformity is less than said predetermined standard.

26. A method of processing a workpiece to be processed according to claim 23, further including the steps, after said step b), of:

c) providing the workpiece to be processed in the reactor chamber;

d) forming an optimized plasma with the process chamber using the set of optimized process parameters determined in said step b); and

e) processing the workpiece to be processed with the optimized plasma.

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