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(54) **Title:** DETECTING A PROCESS ENDPOINT FROM A CHANGE IN REFLECTIVITY

(57) **Abstract:** A substrate processing apparatus comprises a process chamber capable of processing a first material on the substrate. A radiation source is capable of emitting radiation that is reflected from the substrate during processing. A radiation detector is provided to detect the reflected radiation and generate a signal trace. A controller is adapted to receive the signal trace and evaluate an endpoint of processing the first material from a change in the signal trace that is distinctive of an exposure of a second material having a different reflectivity coefficient than the first material.

DETECTING A PROCESS ENDPOINT FROM A CHANGE IN REFLECTIVITY

BACKGROUND

The invention relates to detection of a process endpoint during a substrate fabrication process.

In substrate fabrication processes, semiconductor, dielectric, and conductor materials, including for example materials such as polysilicon, silicon dioxide, aluminum and tungsten silicide, are formed on a substrate by chemical vapor deposition (CVD), physical vapor deposition, oxidation and nitridation processes. For example, in CVD processes, a reactive gas may be used to deposit material on the substrate, and in PVD processes, a target is sputtered to deposit material on the substrate. In oxidation and nitridation processes, an oxide or nitride material, such as silicon dioxide or silicon nitride, respectively, is formed on the substrate by exposing the substrate to a suitable gaseous environment. In subsequent etching processes, a mask of photoresist or hard mask material is formed on the substrate by conventional lithographic methods, and the exposed portions of the substrate are etched by a gas to form patterns of gates, vias, contact holes or interconnect lines. Especially in the etching processes, it is often desirable to change or stop processing of the substrate at a predetermined stage of the process. For example, when etching polysilicon material deposited over features of a silicon nitride mask layer, it is desirable to stop etching when the silicon nitride mask layer is reached and thereafter partially etching polysilicon plugs exposed between the silicon nitride layer. As another example, in the etching of gate structures, it is desirable to stop etching of overlying polysilicon as soon as the underlying gate oxide is reached, especially when the gate oxide is a thin layer.

In plasma emission analysis, an emission spectrum of a plasma in the chamber is analyzed to monitor the etching process as for example taught in U.S. Patent Nos. 4,328,068 and 5,362,256, both of which are incorporated herein by reference. The plasma emission spectrum depends upon the energized plasma species which are dependent upon the composition of the material being etched. When the composition of the material changes, for example, when a layer has completed etching and an underlayer is exposed, the spectral change that occurs in the plasma is used to detect completion of etching of the overlying material. In general, plasma emission methods monitor a predetermined wavelength in the plasma spectral emission and correlate variations in intensity of the wavelength with an endpoint of the process. However, such spectral changes occur only after a large portion of a new material is exposed on the substrate. Thus plasma emission analysis tends to provide information relating to an average state of processing across the surface of the substrate. This may lead to some regions being over-etched while others are under-etched.

Ellipsometry and interferometry are also be used to monitor the etching process. In ellipsometry, a polarized light beam reflected off the substrate being etched is analyzed to determine a phase shift and change in magnitude, as for example disclosed in U.S. Patent Nos. 3,874,797 and 3,824,017, both of which are incorporated herein by reference. In interferometry, a light beam reflected off the substrate is monitored and an etching depth is determined by counting maxima and minima in the amplitude of the reflected beam or from cessation of the signal, as for example disclosed in U.S. Patent No. 4,618,262 to Maydan et al, which is also incorporated herein by reference. The constructive and destructive interference occurs because the light beam is partially reflected off the substrate surface and partially reflected off underlying interfaces. If the original thickness of the layer is known, a remaining thickness may be estimated by counting the maxima/minima peaks during etching. While these methods may be used to estimate the amount of remaining material, it is difficult to precisely determine the end of etching of the material, especially when the original thickness of the material varies slightly from one substrate to another or across the surface of the substrate itself. Also, the area on the substrate from which initial thickness measurements are obtained is often not the same area as that from which the reflected beam is monitored, which may give rises to erroneous measurements.

Thus, it is desirable to precisely detect an endpoint of processing of a material on a substrate, especially to detect an endpoint of etching a layer on a substrate to expose an underlayer. It is further desirable for the endpoint detection method and apparatus to be relatively insensitive to changes in thickness of the layer across the substrate or from one substrate to another.

SUMMARY

Embodiments of the present invention satisfy these needs, in principle, by detecting an endpoint of a process performed on a substrate with accuracy and repeatability. In one aspect, the present invention comprises a substrate processing apparatus comprising a process chamber capable of processing a first material on the substrate. A radiation source is capable of emitting radiation that is reflected from the substrate during processing. A radiation detector is provided to detect the reflected radiation and generate a signal trace. A controller is adapted to receive the signal trace and evaluate an endpoint of processing the first material from a change in the signal trace that is distinctive of an exposure of a second material having a different reflectivity coefficient than the first material.

In one version, the apparatus comprises a computer having a memory capable of operating a computer-readable program embodied on a computer-readable medium, the computer readable program including program code to receive the signal trace and detect the change in the signal trace.

In another aspect, the present invention relates to a method of processing a substrate, in which, the substrate is placed in a process zone, and process conditions are set in the process zone to process a first material on the substrate. Radiation reflected from the substrate during processing is detected and an endpoint of processing the first material is determined from a change in intensity of reflected radiation that is distinctive of exposure of a second material having a different reflectivity coefficient than the first material.

In another aspect, the present invention relates to a substrate processing apparatus comprising a process chamber capable of sustaining a plasma to process a first material on the substrate. A first radiation detector detects a radiation emission from the plasma and generates a first signal, and a second radiation detector detects a reflected radiation from the substrate and generates a second signal. A controller is adapted to receive the first and second signals and determine an endpoint of processing of the first material on the substrate.

In one version, the apparatus comprises a computer having a memory capable of operating a computer-readable program embodied on a computer-readable medium, the computer readable program including program code to receive the first and second signals and determine an endpoint of processing the first material on the substrate.

In another aspect, the present invention relates to a method of processing a substrate, in which, the substrate is placed in a process zone, and a plasma of process gas is formed in the process zone to process a first material on the substrate. Radiation emitted by the plasma and radiation reflected from the substrate are detected. An endpoint of processing the first material is determined from a change in the radiation emitted by the plasma and a change in the radiation reflected from the substrate.

DRAWINGS

These and other features, aspects, and advantages of the present invention will be better understood from the following drawings, description and appended claims, which illustrate exemplary features of the invention, however, it is to be understood that each of the features can be used in the invention in general, not merely in the context of a particular drawing, and the invention includes any combination of these features.

Figure 1a is a schematic sectional view of a substrate showing the partial reflection and partial absorption of incident radiation during processing of a first material on the substrate;

Figure 1b shows the substrate of Figure 1a, after completion of etching of the first material showing radiation being reflected from the surface of an underlying second material;

Figure 2 is a signal trace of the intensity of radiation having a wavelength of 704 nm emitted by the plasma during processing of the substrate;

Figure 3 is a signal trace of the intensity of radiation having a wavelength of 253.7 nm reflected from the substrate during processing of the substrate;

Figure 4 is a schematic sectional side view of a chamber and process monitoring system according to the present invention; and

Figure 5 is an block diagram of the structure of an illustrative computer program suitable for operating the chamber and monitoring the process.

DESCRIPTION

The present invention is useful for monitoring a process conducted on a substrate **20**, and especially useful for detecting an endpoint of processing of a material on the substrate **20**. As illustrated in the example shown in Figures 1a and 1b, the process may be used to detect completion of processing of a first material **22** and exposure of an underlying second material **24**. Generally, the substrate **20** comprises a plurality of materials **22**, **24** formed on a wafer **26** of silicon, compound semiconductor or dielectric. During processing of the materials **22**, **24** it may be desirable to stop processing upon reaching an interface **23** between the first material **22** and the second material **24** or after completion of processing one or both of the first or second materials **22**, **24**. For example, in a typical etching process, it may be desirable to stop etching after etching through the first material **22** or after etching through only a small portion of the underlying second material **24**.

The process may be illustrated referring to a typical etching process, in which a substrate **20** having the layers **22**, **24** is placed in a process zone and process conditions are set for processing the substrate **20** in an energized process gas or plasma, for example to etch the first material **22**. During etching, the plasma emits radiation that is characteristic of the first material **22** being etched, generally, because the plasma contains volatilized gaseous species or compounds of the first material **22** that emit a characteristic spectrum or wavelength of radiation when energized. The intensity fluctuations of radiation having the preselected wavelength is monitored to determine the rate of progress of etching of the first material **22**. Because the radiation intensity (at the preselected wavelength) is dependent upon the amount of material in the plasma that emits radiation in the particular characteristic or signature wavelength, it is also dependent upon the exposed area of the first material **22** and is indicative of the average etching state of the exposed surface of the substrate **20**. Thus, plasma emission analysis allows monitoring of a non-localized or global etching behavior across a substantially the entire substrate **20**.

As an example, Figure 2 shows a trace of the intensity of the plasma emission radiation at a wavelength of 704 nm. The trace represents the radiation intensity observed during etching of a polysilicon layer (first material **22**) overlying a silicon nitride layer (second material **24**). After etching, plugs of polysilicon material **27** are left behind between expanses of the silicon nitride layer **24** and/or exposed silicon **26**. The etching process is performed to clean up polysilicon that is incidentally deposited on the silicon nitride **24** while filing the plugs **27**. Referring to Figure 2, in the first stage I, during etching of the overlying polysilicon **22**, the emission intensity remains relatively flat and at a constant level. The second etching stage II, corresponding to the completion of etching of the underlying silicon nitride **24**, shows a peak in the intensity of radiation emissions having the preselected wavelength. When all the underlayer **24** is etched away, the radiation intensity drops down to another level in stage III, in which the substrate **26** is being etched. The plasma emission curve allows the operator to select a point **29** at which the slope of the radiation emission curve begins to rise (which indicates commencement of etching of the underlayer **24**) to determine the endpoint of etching of the overlayer **22**.

In addition to the plasma emission analysis, the intensity of radiation reflected from the surface of the substrate **20** is also monitored. In this method, radiation incident on the substrate **20** is partially absorbed and partially reflected from the materials **22**, **24** that are being processed on the substrate **20**. Generally, referring to Figure 1a, when an optically absorbing material **22** (medium 1) lies on another material **24** (medium 2), the absorption and reflectivity of radiation may be approximately described by a summation equation. The radiation in the process environment (medium 0) that is incident on the material **22** has a first surface reflection determined by the complex Fresnel coefficient $\mathbf{r}_1 = (\mathbf{n}_0-\mathbf{n}_1)/(\mathbf{n}_0+\mathbf{n}_1)$ where $\mathbf{n}_0$ and $\mathbf{n}_1$ are the complex refractive indices of media 0 and 1. The complex refractive index **n** is defined as $\mathbf{n} = \mathbf{n} - \mathbf{ik}$ where **n** and **k** are the real and imaginary parts, being the refractive index and extinction coefficient, respectively. As shown in Figure 1a, when the material **22** has a certain thickness, a portion of the incident radiation **76** is reflected as the component **78** and another portion is transmitted into the material **22** according to the complex Fresnel transmission coefficient $\mathbf{t}_1 = 2\mathbf{n}_0/(\mathbf{n}_0+\mathbf{n}_1)$. The transmitted radiation is absorbed in the material **22** as a function of the depth *d* by the factor $\exp(-4Bk_1d/8)$ where 8 is the wavelength of the incident radiation. If the incident radiation has not been fully absorbed before reaching the interface **23** at the rear of the material **22** some of the radiation is reflected back according to the equation, $\mathbf{r}_2 = (\mathbf{n}_1-\mathbf{n}_2)/(\mathbf{n}_1+\mathbf{n}_2)$, where $\mathbf{n}_2$ is the complex refractive index for material **22**. The part of the reflection which remains after absorption during the round trip is transmitted back into process environment -- where it combines with the original reflected radiation but with a phase change $* = 2\ \mathrm{B}\ n_1\ d_1/8$ which depends upon the round trip distance covered in the depth *d*. The net reflected amplitude is approximately, $\mathbf{r}_{net}\ ñ\ \mathbf{r}_1 + \mathbf{t}_1\ \mathbf{t}_1'\ \mathbf{r}_2 \exp(+2i*) \exp(-4\mathrm{B}k_1d/8)$, where multiple reflections have been neglected. Explicit formulations may be found in references such as M. Born and E. Wolf, Principles of Optics, Pergamon Press (1965), which is incorporated herein by reference. When *d* and k_1 are large enough, absorption dominates and the second term is essentially zero, producing a constant net reflection as a function of thickness. However, when the material **22** is completely etched, for example, as shown in Figure 1b, there is a net reflection from the surface of the underlying silicon nitride material **24** and the remaining surface of the polysilicon plug **27** that contributes to the total amplitude or intensity of the reflected radiation. In between, the amplitude of the reflected radiation may vary from the changing phase and magnitude of the second term through the interface between the two materials, and as the thickness *d* is changed. Depending on the magnitude of k_1, the variation in total reflected intensity with d_1 can appear periodic, with an increasing amplitude as d_1 tends to zero. After the first material has been etched and entirely removed, the incident radiation **76** is partially reflected from the surface of the polysilicon plugs **27** and partially reflected from the surface of the silicon nitride material **24**, and additional multiple internal reflections may occur from underlying layers and interfaces (not shown). The sum of the reflected components results in another observed amplitude of reflected radiation that may be different from the previously observed periodic variation in intensity.

Figure 3 shows the amplitude trace of reflected radiation obtained during etching of the same type of substrate **20** as that described above, namely one with polysilicon **22** overlying silicon nitride **24**. In this example, a wavelength of 253.7 nm was chosen to irradiate the substrate **20** because it is one of the peak amplitudes of radiation of an emission spectra from a mercury discharge lamp. In the first stage I, during etching of the overlying polysilicon layer **22**, the intensity of the reflected radiation remains relatively flat. The second etching stage II, corresponding to the etching of the underlying silicon nitride layer **24**, shows a minima peak having a downward slope that corresponds to the etching away or clear-off of residual regions of polysilicon left in the field of view of the sensor. After the silicon nitride layer is exposed, the polysilicon plug **27** is etched at a faster rate than the surrounding silicon nitride **24**. As a result, there is a difference in path length for the radiation reflected from the surface of the polysilicon plug **27** relative to the radiation reflected from the surface of the silicon nitride **24**, which gives rise to periodic variations that correspond to maxima and minima interference peaks. This type of curve may be used to detect a precise endpoint of completion of etching of the polysilicon overlayer **22** and onset of etching of the underlayer **24** (at the point **31** where the curve has sloped downward for a short time period) to ensure complete removal of residual polysilicon. This is advantageous because it allows selection of a different gas chemistry when the polysilicon **22** is substantially entirely etched away, to allow etching away of a portion of the plug **27** with a different gas chemistry that, for example, may have a higher etching selectivity to etching silicon nitride relative to polysilicon.

Thus, the intensity of the reflected radiation may be monitored and evaluated to determine a change in amplitude of reflected radiation that occurs during processing of the first and second materials **22**, **24** from the difference in reflectivity between one or more of the first material **22**, second material **24**, or their interface **23**. For example, when radiation passes through the first and second materials **22**, **24**, the second material **24** may have a different reflectivity coefficient or function than the first material **22** which would cause a smaller or larger percentage of radiation to be reflected from the surface of the second material **24** than that reflected from the first material **22**. In addition, the interface **23** may also have a different reflectivity coefficient or function than the materials **22**, **24** which would affect the amount of radiation reflected from the interface **23**. The empirically observed change in the amplitude trace is precisely correlated to the change in reflectivity that occurs after etching through one layer **22** and at the interface **23** of a second layer **24**. This is typically a precise and sharply defined change that it is believed results substantially only from the change in reflectivity coefficient of the two materials and may be used to pinpoint the endpoint of the etching of the first layer **22** and reaching the environment of etching the second layer **24** accurately and decisively.

Additional precision may be obtained by focusing the incident radiation onto a precise area or region of the substrate **20** containing a known thickness of polysilicon material **22**. The localized reading of the change in reflectivity at the completion of etching of the localized region provides especially useful information when evaluated together with the average or global reading obtained across the surface of the substrate **20** by plasma emission analysis. The two readings are evaluated to determine both the average etching rate and local etching rate, and are concurrently detected to chose an endpoint which is more accurate than a single reading from any one of the methods. In addition, the two readings may be used to determine if there is any deviation in etching rates or in the original thickness of the polysilicon layer from substrate to substrate or across a batch of substrates. A particular set of measurements may be empirically determined as a reference point for a batch of substrates. When future measurements on other batches deviate from these reference values, it could mean that the thickness of one of the materials **22**, **24** has changed and the endpoint time should be adjusted in accordance with the deviation.

While the relationship between the amplitude change of reflected radiation in the etching of a first material **22** and exposure of a second material **24** may be established based on empirical data, it may also be estimated by a radiation absorption model with the appropriate parameters and assumptions, and knowing values for other parameters of the first and second materials **22**, **24**, e.g., its composition, refractive index, extinction coefficient, thickness, and other radiation absorption and reflection constants; an etch rate and etching selectivity of the process; and an area of overlying mask material. A trace of the estimated amplitude change may be mathematically calculated for given thicknesses of the first and second materials and be stored as a reference trace or as a table of values. The reference trace or values in the table may be compared against an empirically determined signal trace to determine the stage or endpoint of the etching process.

The examples provided herein, may be used, for example, in the etching of a substrate **20** in the apparatus **27** that is schematically illustrated in Figure 4. Generally, the apparatus **27** comprises a chamber **28** having a process zone **30** for processing the substrate **20** and a support **32** to receive the substrate **20** in the process zone **30**. The process gases are introduced into the chamber **28** through a gas supply **34** comprising a gas source **36**, gas outlets **38** located around the periphery of the substrate **20** (as shown) or in a showerhead mounted on the ceiling of the chamber (not shown), and a gas flow controller **40** for controlling the flow rate of the process gas. Spent process gas and etchant byproducts are exhausted from the chamber **28** through an exhaust **42** comprising roughing and turbomolecular pumps (not shown) and a throttle valve **44** is used to control the pressure of process gas in the chamber **28**.

An energized gas or plasma is generated from the process gas by a gas energizer **46** that couples RF or microwave energy to the process gas in the process zone **30** of the chamber **28**, such as for example, an inductor antenna **48** comprising one or more coils powered by an antenna power supply **50** to inductively couple RF energy to the chamber **28**. In addition, a first process electrode **50** such as an electrically grounded sidewall of the chamber **28** and a second electrode **52** such as an electrically conductor below the substrate **20** may be used to further energize the gas in the chamber **28**. The first and second electrodes **50**, **52** are electrically biased relative to one another by an RF voltage provided by an electrode voltage supply **54**. The frequency of the RF voltage applied to the inductor antenna **48** and the electrodes **50**, **52** is typically from about 50 KHz to about 60 MHz.

The chamber **28** further comprises a process monitoring system **56** to monitor the process being performed on the substrate **20**. The interferometric analysis system **56** comprises both an interferometric analysis system **56** and a plasma emission analysis system **57**. The radiation source **58** may provide radiation such as ultraviolet (UV), visible or infrared radiation; or may provide other types of radiation such as X-rays. The radiation source **58** may comprise, for example, an emission from a plasma generated inside the chamber **28**, the plasma emission being generally multispectral, i.e., providing radiation having multiple wavelengths extending across a spectrum, such as polychromatic radiation. The radiation source **58** may also be positioned outside the chamber **28** so that a radiation beam **60** may be transmitted from the source **58** through a window **61** and into the chamber **28**. The radiation source **58** may also provide substantially monochromatic radiation having predominant wavelengths, or a single wavelength such as monochromatic light for example, a He-Ne or Nd-YAG laser. Alternatively, the radiation source **58** may provide radiation having multiple wavelengths, such as polychromatic light, which may be selectively filtered to a single wavelength. Suitable radiation sources **58** for providing polychromatic light include Hg discharge lamps that generate a polychromatic light spectrum having wavelengths in a range of from about 180 to about 600 nanometers; arc lamps such as xenon or Hg-Xe lamps and tungsten-halogen lamps; and light emitting diodes (LED).

In one version, the radiation source **58** provides a source of non-polarized light, such as ultraviolet, infrared or visible light directly above the substrate **20**. One reason is that variations in the intensity of polarized radiation reflected from the substrate **20** can be masked by changing absorption characteristics of the energized gas or plasma. In addition, the state of polarization of the radiation also influences its absorption in materials having oriented crystalline structures, such as crystals having other than cubic symmetry. Also, the polarization state of the radiation can change when it passes through a thin residue film that deposits on the window **61** of the chamber **28** during the process, and the polarization state also changes as the thickness of the residue film increases, which gives rise to erroneous measurements. Thus, for certain processes, depending on the process gas composition and the location of the source of radiation, it may be preferred to use a radiation source **58** providing unpolarized radiation. A normal incidence of the radiation onto the substrate **20** can reduce such effects. Normal incidence also provides a more accurate endpoint reading for a substrate **20** having tall and narrowly spaced features over the layers **22, 24**, because the normally incident radiation is not blocked from reaching the layers **22, 24** by the height of the narrow features. However, the normal incidence is not necessary for detection of the reflected radiation and other angles of incidence may be employed.

The interferometric system **56** further comprises a radiation detector **62** for detecting radiation **64** reflected by the substrate **20**. The radiation detector **62** comprises a radiation sensor, such as a photovoltaic cell, photodiode, photomultiplier, or phototransistor, which provides an electrical output signal in response to a measured intensity of a reflected beam of radiation **64** (or an emission spectra from the plasma). The signal may comprise a change in the level of a current passing through an electrical component or a change in a voltage applied across an electrical component. A suitable system for coupling the radiation detector **62** to the chamber **28** comprises a fiberoptic cable **69** leading to the sensor of the radiation detector **62**. The process endpoint data processed by the detectors **62** is transmitted to an interferometric analyzer **65** appropriate through interface boards to allow analysis of the data.

Optionally, a lens assembly **66** may be used to focus a radiation beam **60** emitted by the radiation source **58** onto the substrate **20**, or to focus a radiation beam **64** reflected back from the substrate **20** onto the sensor of the radiation detector **62**. For example, for a radiation source **58** comprising a Hg-discharge lamp located outside the chamber **28**, a plurality of lenses **66** may be used to focus a radiation beam **60** from the lamp through the window **61** and onto a beam spot **70** on the substrate **20**. The area of the beam spot **70** should be sufficiently large to provide an accurate measurement of the surface topography of the substrate **20**. The lenses **66** may also be used to focus reflected radiation **64** back onto the sensor of the radiation detector **62** in the reverse direction which is especially useful when the radiation source **58** is a plasma emission.

Optionally, a positioner **72** may be used to scan the incident radiation **60** across the substrate surface to locate a suitable portion of the substrate **20** on which to "park" the beam spot **70**. The positioner **72** may comprise one or more primary mirrors **74** that can rotate at small angles to deflect radiation from the radiation source **58** onto different positions of the substrate surface (as shown). Alternatively, the mirrors **74** can also direct radiation emitted from a plasma emission and at least partially reflected off the substrate **20** back onto the radiation detector **62**. Additional secondary mirrors (not shown) may be used to intercept and focus reflected radiation back on the radiation detector **62**. The positioner **72** can also be used to scan radiation in a raster pattern across the substrate **20**. In this version, the positioner **72** further comprises a movable stage (not shown) upon which the radiation source **58**, lens assembly **66**, and radiation detector **62** are mounted. The movable stage may be moved through set intervals by a drive mechanism, such as a stepper motor, that scans or otherwise moves the beam spot **70** across the substrate **20**.

Radiation having a plurality of wavelengths, such as polychromatic light from a lamp or a plasma emission spectra, can be suitable filtered by placing a filter **76** in the path of the incident or reflected radiation **60**, **64**. The filter **76** is typically located in the lens assembly **66** but can also be located at other positions in the chamber **28**, for example, in the chamber window **61**, in front of the radiation detector **62**, or in front of the radiation source **58**. A suitable filter **76** comprises thin films on a transparent support that selectively transmit radiation having the desired wavelength, a filtering lens, a diffraction grating having a diffraction spacing that scatters radiation having undesirable wavelengths, attenuation of radiation through a long pathlength in a partially absorbing material, or selective electronic filtering of the signal from the radiation detector **62** to read only the portion of the signal corresponding to radiation having the desired wavelength.

The plasma emission analysis system **57** comprises a monochromator **80**, a stepper motor **82** that controls the wavelength selection for the monochromator **80**, and a calibration lamp **84** that calibrates the monochromator **80**. The monochromator **80** converts the radiation signal into an electrical signal which is amplified by a photomultiplier **86** powered by a high voltage power source **88**. The output of the photomultiplier **86** is coupled to the monochromator interface board **90**. The stepper motor **82** allows selection of a particular wavelength for monitoring the process being conducted on the substrate **20** controlling the position of an interference grid within the monochromator **80** to select a wavelength. The interface board **90** is also coupled to the calibration lamp **84** to calibrate the monochromator **80** at a particular wavelength. Alternatively, the monochromator-based system can be replaced by a bandpass photon detector system, such as the system disclosed in U.S. Patent Application No. 08/800,003, filed February 13, 1997, and incorporated herein by reference. The radiation data is supplied to an analyzer **94** through an electronic interface board 189. The analyzer **94** may be a spectrometer that separates the components of the radiation emanating from the chamber **28**, according to their frequency or wavelength. Such analyzers include, but are not limited to, grating spectrometers, prism spectrometers, and band pass screen arrays, for example, a HOT pack manufactured by Applied Materials, Inc. of Santa Clara, California. Alternatively, the analyzer may be a component of the detector, controller, or other such devices.

The chamber and endpoint detection system **56** is operated by a controller **100** that executes a computer-readable process control program **102** on a computer system **104** comprising a central processor unit (CPU) **106**, such as for example a 68040 microprocessor, commercially available from Synergy Microsystems, California, or a Pentium Processor commercially available from Intel Corporation, Santa Clara, California, that is coupled to a memory **108** and peripheral computer components. The memory **108** comprises a computer-readable medium having the computer-readable program **102** embodied therein. Preferably, the memory **108** includes a hard disk drive **110**, a floppy disk drive **112**, and random access memory **114**. The computer system **104** further comprises a plurality of interface cards including, for example, analog and digital input and output boards, interface boards, and motor controller boards. The interface between an operator and the computer **104** can be, for example, via a display **118** and a light pen **120**. The light pen **120** detects light emitted by the monitor **118** with a light sensor in the tip of the light pen **120**. To select a particular screen or function, the operator touches a designated area of a screen on the display **118** and pushes the button on the light pen **120**. Typically, the area touched changes color, or a new menu is displayed, confirming communication between the user and the controller **110**. The computer **104** communicates with the chamber **28** and process monitoring systems **56, 57** via a controller interface **116** which has a plurality of interface boards and other cards.

The computer-readable program **102** stored on the memory **108** or other computer program product inserted in the disk drive **112**, may also be used to operate the controller **100**. The computer program **102** generally comprises software to operate the chamber **28** and its components to monitor the processes, to activate safety systems, and other control software. The computer program **102** may be written in any conventional programming language, such as for example, assembly language, C^{++}, Pascal, or Fortran. Suitable program code is entered into a single file, or multiple files, using a conventional text editor and stored or embodied in the memory **108** of the computer system **104**. If the entered code text is in a high level language, the code is compiled, and the resultant compiler code is then linked with an object code of precompiled library routines. To execute the linked, compiled object code, the user invokes the object code, causing the CPU **106** to read and execute the code to perform the tasks identified in the program.

Figure 5 is an illustrative block diagram of a hierarchical control structure of an exemplary embodiment of a computer program **102** according to the present invention. Using a light pen interface, a user enters a process set and chamber number into a process selector program **132** in response to menus or screens displayed on the CRT terminal. The process sets are predetermined groups of process conditions necessary to carry out a process in a chamber **28** including without limitations, gas composition, gas flow rates, temperature, pressure, gas energizer settings such as RF or microwave power levels, cooling gas pressure, and wall temperature. In addition, parameters needed to operate the process monitoring systems **56**, **57** are also inputted by a user into the process selector program. These parameters include known properties of the materials being processed, especially radiation absorption and reflection properties, such as reflectance and extinction coefficients; process monitoring algorithms that are modeled from empirically determined data; tables of empirically determined or calculated values that may be used to monitor the process; and properties of the materials being processed on the substrate.

The process sequencer program **134** comprises program code to accept a process chamber **28** and set of process parameters from the process selector program **132** and to control its operation. The sequencer program **134** initiates execution of the process set by passing the particular process parameters to a chamber manager program **136** that controls multiple processing tasks in the process chamber **28**. The process chamber program **124** includes program code to set the timing, gas composition, gas flow rates, chamber pressure, chamber temperature, RF power levels, support position, heater temperature, and other parameters of a particular chamber **28**. Typically, the process chamber program **124** includes a substrate positioning program **138**, a gas flow control program **140**, a gas pressure control program **142**, and a gas energizer control program **144**. Typically, the substrate positioning program **138** comprises program code for controlling chamber components that are used to load the substrate **20** onto the support **32** and optionally, to lift the substrate **20** to a desired height in the chamber **28** to control the spacing between the substrate **20** and the gas outlets **38** of the gas supply system **34**. The process gas control program **140** has program code for controlling the flow rates of different constituents of the process gas. The gas flow control program **140** controls the open/close position of the safety shut-off valves, and also ramps up/down the gas flow controller **40** to obtain the desired gas flow rate. The gas pressure control program **142** comprises program code for controlling the gas pressure in the chamber **28** by regulating the aperture size of the throttle valve **44** in the exhaust system **42** of the chamber. The gas energizer control program **144** comprises program code for setting low and high-frequency RF power levels applied to the process electrodes **51**, **52** in the chamber **28**. Optionally, the heater control program **146** comprises program code for controlling the temperature of a heater element (not shown) used to resistively heat the support **32** and substrate **20**.

The process monitoring program **126** comprises program code that obtains sample or reference signals from the plasma emission analyzer **94** or the interferometry analyzer **65** and processes the signal according to preprogrammed criteria. Typically, a radiation amplitude or spectrum trace is provided to the controller **100**. The process monitoring program **126** may also send instructions to the controller **100** to operate components such as the radiation source **58**, radiation detector **62**, the positioner **72**, lens assembly **66**, filter **76**, and other components. The program may also send instructions to the chamber manager program **136** or other programs to change process conditions or other chamber settings.

To define the parameters of the process monitoring program **126**, initially, one or more substrates **20** having predetermined thicknesses of material are selected for processing. Each substrate **20** is placed at one time into the process chamber **28** and process conditions are set to process a material **22** or an underlying material **24** on the substrate **20**. Radiation reflected from the substrate **20** and/or emitted from the plasma in the chamber **28** are monitored using one or more radiation detectors **62**. After a series of such traces are developed, they are examined to identify a recognizable change in a property of the trace, which is used as input for the computer program, in the form of an algorithm, a table of values, or other criteria for suitable for evaluating an event in the chamber **28** or a property of the substrate **20**. For example, the process monitoring program **126** may include program code to evaluate a signal corresponding to a plasma emission or to an intensity of reflected radiation **64** which may be used to detect completion of processing of a material on the substrate **20**. Thus, the computer program **126** comprises program code to evaluate first and second signals that correspond to radiation emitted from the plasma and reflected from the substrate **20**. The program code evaluates an incoming signal trace provided by the analyzers **65**, **94** and determines a process endpoint or completion of a process stage when a desired set of criteria is reached, such as when an attribute of the detected signal is substantially similar to a pre-programmed value. The computer program **126** may also be programmed to detect both a completion of processing of a material, for example, by detecting a change in amplitude or a rate of change of amplitude of emitted or reflected radiation. The desired criteria are programmed into process monitoring program **126** as preset or stored parameters, algorithms, or tables of values. The program **126** may also include program code for modeling a trace of radiation, selecting a feature from the modeled trace or allowing a user to select the feature, storing the modeled trace or the feature, detecting a portion of an incoming signal, evaluating the measured signal relative to the stored trace or feature, and calling an end of a process stage of the process being performed on the substrate **20** or display.

In one version, the process monitoring program **126** comprises program code for continuously analyzing a trace of a measured amplitude of radiation by drawing a box or "window" around the end portion of the trace and back in time, with signal height and time length established in the preprogrammed algorithm. A set of windows may be programmed to detect a valley or peak in the trace, trigger on an upward slope to detect a later endpoint, or to trigger on a downward slope to detect an endpoint before a valley in the trace. The first criterion is met when the signal in the trace becomes too steep and exits or moves out of the preprogrammed box ("WINDOW OUT") or when it becomes gradual and enters the box ("WINDOW IN"). Additional windows are sequentially applied on the moving trace to generate the complete set of criteria to make a determination on whether the change in signal measured in the real time trace is an endpoint of the process, a change in thickness of the material, or is only noise. The direction of entering or exiting a box may also be specified as part of the preprogrammed input criteria for operating the process monitoring program **126**. Upon detecting an onset or completion of a process, the process monitoring program **126** signals the process chamber program **126** which sends instructions to the controller **100** to change a process condition in a chamber **28** in which the substrate **20** is being processed. The controller **100** is adapted to control one or more of the gas supply **34**, plasma generator **46**, or throttle valve **44** to change a process condition in the chamber **28** in relation to the received signal.

The present invention is described with reference to certain preferred versions thereof, however, other versions are possible. For example, the endpoint detection process can be used for detecting endpoints in other processes and in other chambers as would be apparent to one of ordinary skill, including without limitation, other types of etching chambers, such as capacitively coupled chambers; ion implantation chambers; and deposition chambers such as PVD or CVD chambers. Therefore, the spirit and scope of the appended claims should not be limited to the description of the preferred versions contained herein.

What is claimed is:

1. A substrate processing apparatus comprising:

a process chamber capable of processing a first material on the substrate;

a radiation source capable of emitting radiation that is reflected from the substrate during processing;

a radiation detector to detect the reflected radiation and generate a signal trace; and

a controller adapted to receive the signal trace and determine an endpoint of processing the first material from a change in the signal trace that is distinctive of an exposure of a second material having a different reflectivity coefficient than the first material.

2. An apparatus according to claim 1 wherein the change in the signal trace corresponds to a change in intensity of the signal trace.

3. An apparatus according to claim 1 wherein the change in intensity results substantially entirely from a change in reflectivity coefficient.

4. An apparatus according to claim 1 wherein the substrate comprises first and second materials, and wherein processing conditions are set to etch the first material until exposure of the second material.

5. An apparatus according to claim 1 wherein the controller comprises a computer having a memory capable of operating a computer-readable program embodied on a computer-readable medium, the computer readable program including program code to detect a change in intensity that results substantially entirely from the change in reflectivity.

6. An apparatus according to claim 1 wherein the radiation source is adapted to provide non-polarized radiation.

7. An apparatus according to claim 6 wherein the radiation source comprises a laser, LED or lamp.

8. An apparatus according to claim 1 wherein the radiation source is mounted above the substrate to direct a radiation beam at an incident angle of about 80 to 90 degrees onto the substrate.

9. A substrate processing apparatus comprising:

(a) a chamber capable of processing a first material on the substrate;

(b) a radiation source capable of emitting non-polarized radiation that is reflected from the substrate during processing;

(c) a radiation detector to detect the reflected radiation and generate a signal trace; and

(d) a computer having a memory capable of operating a computer-readable program embodied on a computer-readable medium, the computer readable program including program code to receive the signal trace and detect a change in the signal trace that is distinctive of exposure of a second material having a different reflectivity than the first material.

10. An apparatus according to claim 9 wherein the computer readable program includes program code to determine a change in intensity of the signal trace.

11. A method of processing a substrate in a process zone, the method comprising the steps of:

(a) placing the substrate in the process zone;

(b) setting process conditions in the process zone to process a first material on the substrate;

(c) detecting radiation reflected from the substrate during processing; and

(d) determining an endpoint of processing of the first material from a change in intensity of reflected radiation that is distinctive of exposure of a second material having a different reflectivity than the first material.

12. A method according to claim 11 wherein the change in intensity results substantially entirely from a change in reflectivity coefficient from the first to the second material.

13. A method according to claim 11 further comprising directing a beam of non-polarized radiation onto the substrate.

14. A method according to claim 13 comprising directing the radiation beam at an incident angle of about 80 to 90 degrees onto the substrate.

15. A method according to claim 11 comprising setting process conditions to etch the first material to expose the second material.

16. A substrate processing apparatus comprising:

a process chamber capable of sustaining a plasma to process a first material on the substrate;

a first radiation detector to detect a radiation emission from the plasma and generate a first signal;

a second radiation detector to detect a reflected radiation from the substrate and generate a second signal; and

a controller adapted to receive the first and second signals and determine an endpoint of processing of the first material on the substrate.

17. An apparatus according to claim 16 wherein the controller is adapted to evaluate the first signal to determine an averaged state of etching of the substrate.

18. An apparatus according to claim 16 wherein the controller is adapted to evaluate the second signal to determine a change in the second signal that is distinctive of the exposure of a second material having a different reflectivity coefficient than the first material.

19. An apparatus according to claim 16 wherein the change in the second signal comprises a change in intensity that results substantially entirely from a change in reflectivity coefficient.

20. An apparatus according to claim 16 wherein the substrate comprises first and second materials, and wherein processing conditions are set to etch the first material until exposure of the second material.

21. A substrate processing apparatus comprising:

a process chamber capable of sustaining a plasma to process a first material on the substrate;

a first radiation detector to detect a radiation emission from the plasma and generate a first signal;

a second radiation detector to detect a reflected radiation from the substrate and generate a second signal; and

a computer having a memory capable of operating a computer-readable program embodied on a computer-readable medium, the computer readable program including program code to receive the first and second signals and determine an endpoint of processing the first material on the substrate.

22. An apparatus according to claim 21 wherein the computer readable program includes program code to evaluate the first signal to determine an averaged state of etching of the first material, and to evaluate the second signal to determine a change in signal that is distinctive of exposure of a second material having a different reflectivity coefficient than the first material.

23. A method of processing a substrate in a process zone, the method comprising the steps of:

(a) placing the substrate in the process zone;

(b) forming a plasma of process gas in the process zone to process a first material on the substrate;

(c) detecting radiation emitted by the plasma;

(d) detecting radiation reflected from the substrate; and

(e) determining an endpoint of processing the material from a change in the radiation emitted by the plasma and a change in the radiation reflected from the substrate.

24. A method according to claim 23 comprising evaluating a change in radiation emitted by the plasma to determine an averaged state of etching of the substrate.

25. A method according to claim 23 comprising identifying a distinctive change in radiation reflected from the substrate to determine exposure of a second material having a different reflectivity coefficient than the first material.

26. A method according to claim 23 comprising identifying a distinctive change in radiation that substantially entirely results from a change in reflectivity coefficient of the substrate.

27. A method according to claim 23 comprising setting process conditions to etch the first material to expose a second material.

28. A method according to claim 23 further comprising directing non-polarized radiation onto the substrate.

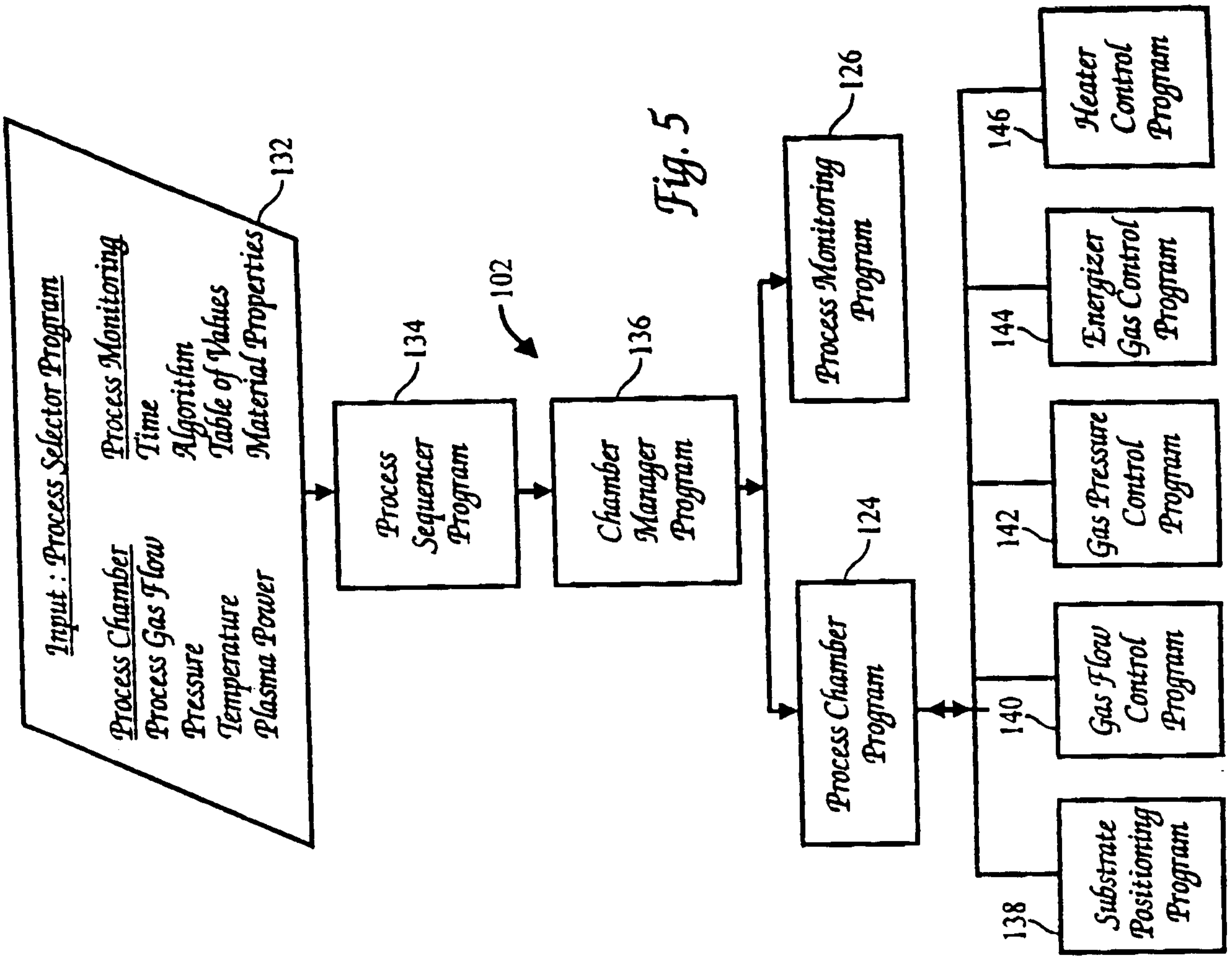

Fig. 5

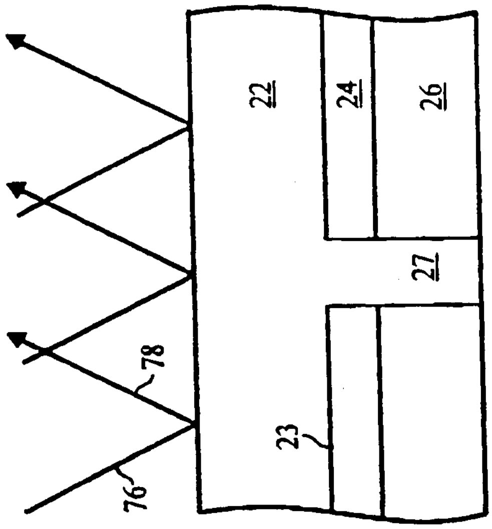

Fig. 1a

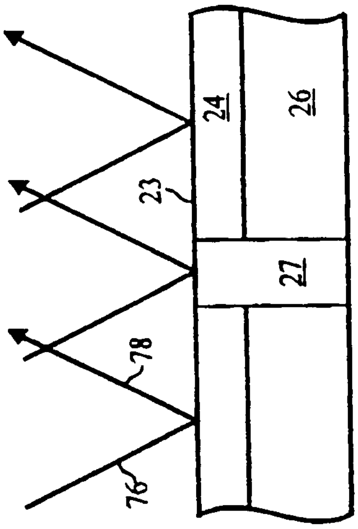

Fig. 1b

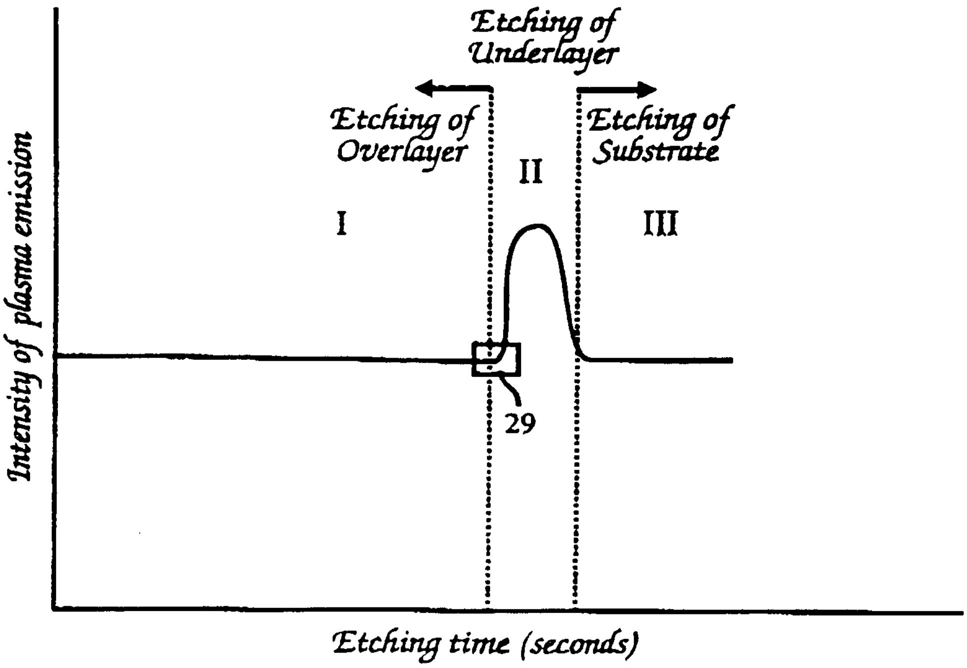
Etching of Underlayer
Etching of Overlayer
Etching of Substrate
I
II
III
29
Intensity of plasma emission
Etching time (seconds)

Fig. 2

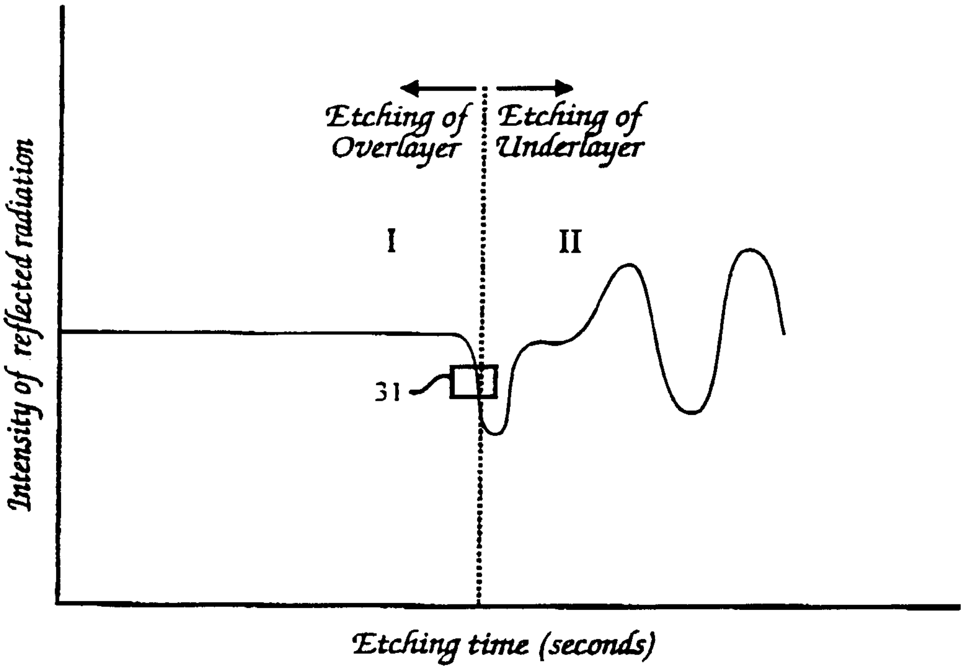
Etching of Overlayer
Etching of Underlayer
I
II
31
Intensity of reflected radiation
Etching time (seconds)

Fig. 3

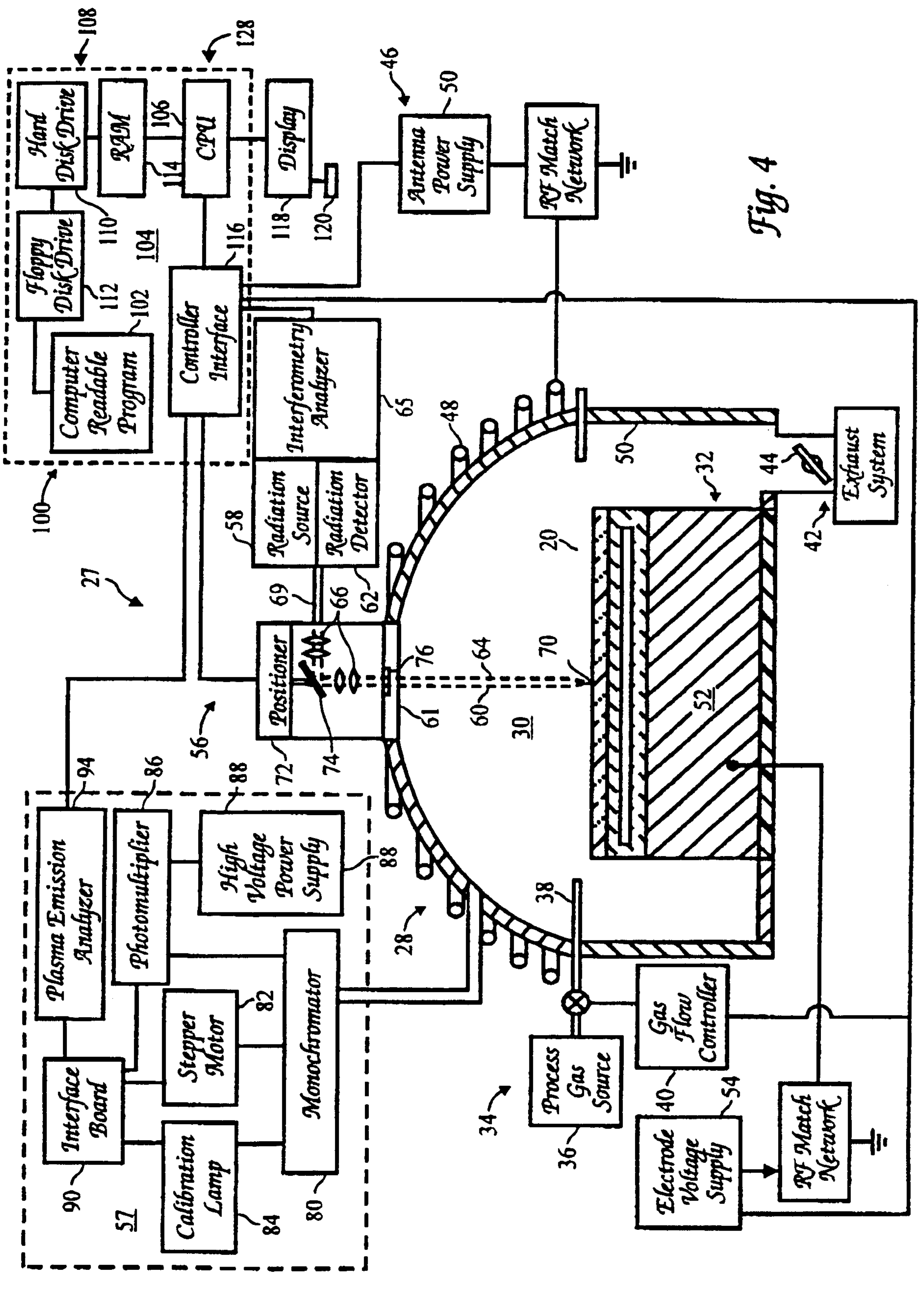
108
128
Hard Disk Drive
RAM
CPU
Display
Floppy Disk Drive
Computer Readable Program
Controller Interface
110
106
114
112
104
102
116
118
120
100
46
50
Antenna Power Supply
RF Match Network
Interferometry Analyzer
65
48
50
Radiation Source
Radiation Detector
58
62
69
66
27
32
20
44
42
Exhaust System
Positioner
56
72
74
76
61
64
60
70
30
52
94
86
88
Plasma Emission Analyzer
Photomultiplier
High Voltage Power Supply
88
38
28
Stepper Motor
82
Monochromator
Interface Board
Calibration Lamp
90
57
84
80
Process Gas Source
Gas Flow Controller
34
36
40
54
Electrode Voltage Supply
RF Match Network

Fig. 4