US 20120291952A1

(19) United States

(12) Patent Application Publication

(10) Pub. No.: US 2012/0291952 A1

(43) Pub. Date: Nov. 22, 2012

Davis et al.

(54) METHOD AND SYSTEM FOR MONITORING AN ETCH PROCESS

(76) Inventors: **Matthew Fenton Davis**, Brookdale, CA (US); **John M. Yamartino**, Palo Alto, CA (US); **Lei Lian**, Santa Clara, CA (US)

(21) Appl. No.: **13/564,963**

(22) Filed: **Aug. 2, 2012**

Related U.S. Application Data

(62) Division of application No. 10/674,568, filed on Sep. 29, 2003, now Pat. No. 8,257,546.

(60) Provisional application No. 60/479,601, filed on Jun. 18, 2003, provisional application No. 60/462,493, filed on Apr. 11, 2003, provisional application No. 60/490,795, filed on Jul. 28, 2003.

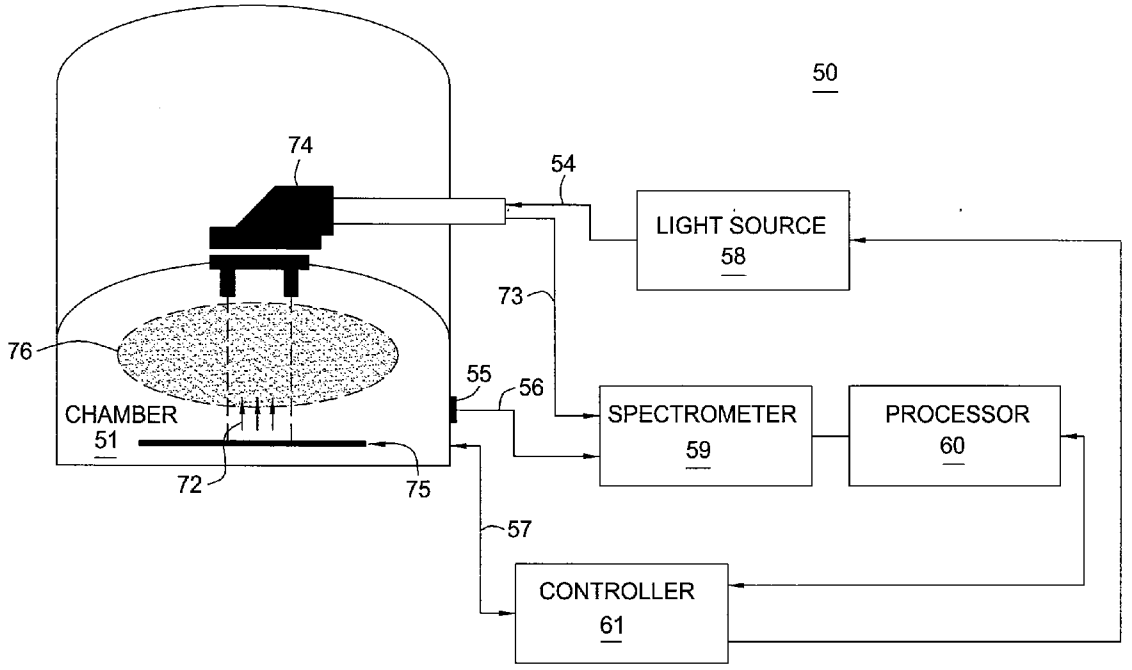
Publication Classification

(51) **Int. Cl.**
G06F 15/00 (2006.01)
B44C 1/22 (2006.01)

(52) **U.S. Cl.** **156/345.25**; 702/189

(57) **ABSTRACT**

A method and apparatus for monitoring an etch process. The etch process may be monitored using measurement information (e.g., critical dimensions (CD), layer thickness, and the like) provided ex-situ with respect to the etch process in combination with in-situ monitoring (e.g., spectroscopy, interferometry, scatterometry, reflectometry, and the like) performed during the etch process. The ex-situ measurement information in combination with the in-situ monitoring may be used to monitor for example, an endpoint of an etch process, an etch depth profile of a feature formed on a substrate, fault detection of an integrated circuit manufacturing process, and the like.



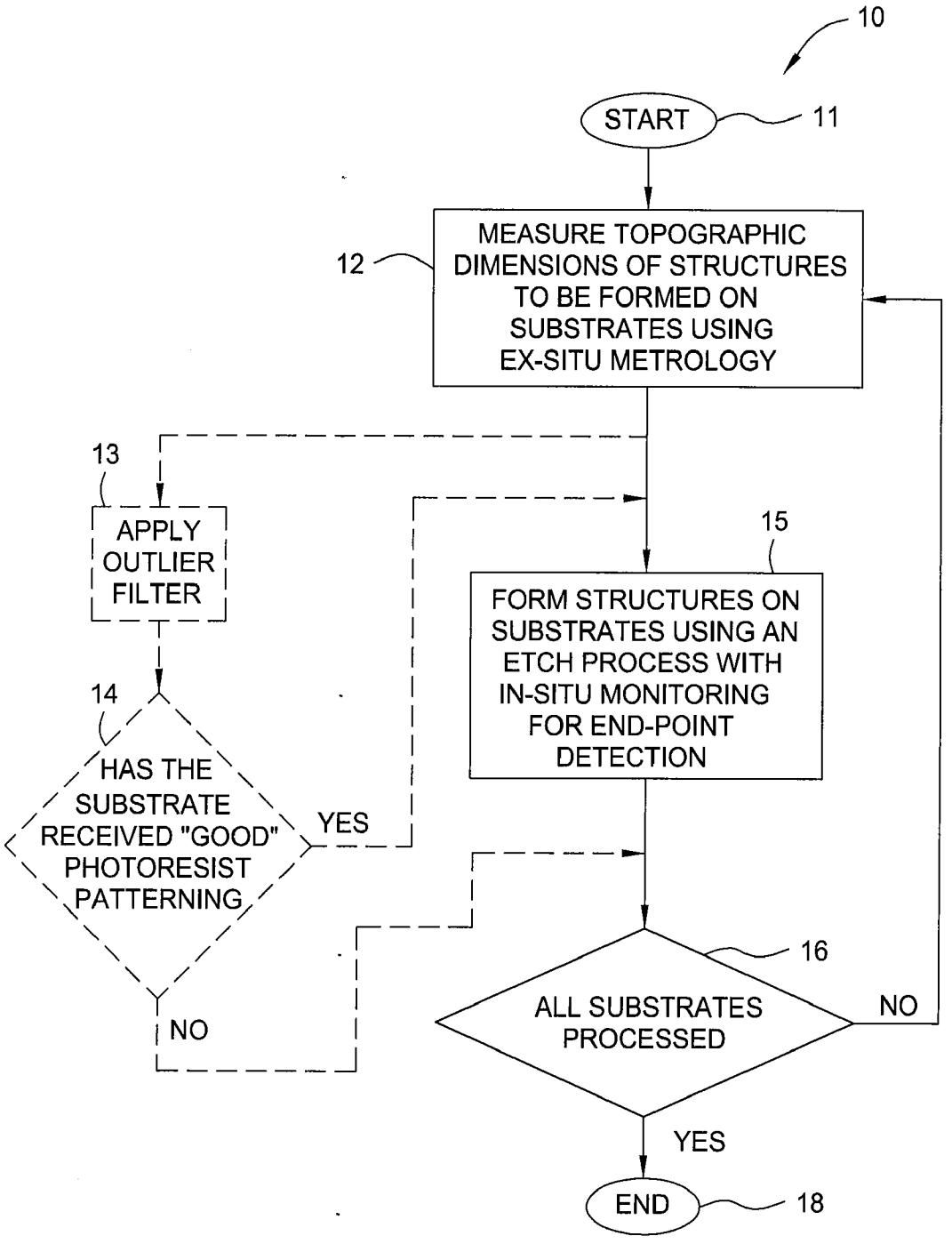

10
START
11
MEASURE TOPOGRAPHIC DIMENSIONS OF STRUCTURES TO BE FORMED ON SUBSTRATES USING EX-SITU METROLOGY
12
13
APPLY OUTLIER FILTER
15
FORM STRUCTURES ON SUBSTRATES USING AN ETCH PROCESS WITH IN-SITU MONITORING FOR END-POINT DETECTION
14
HAS THE SUBSTRATE RECEIVED "GOOD" PHOTORESIST PATTERNING
YES
NO
16
ALL SUBSTRATES PROCESSED
NO
YES
END
18

FIG. 1

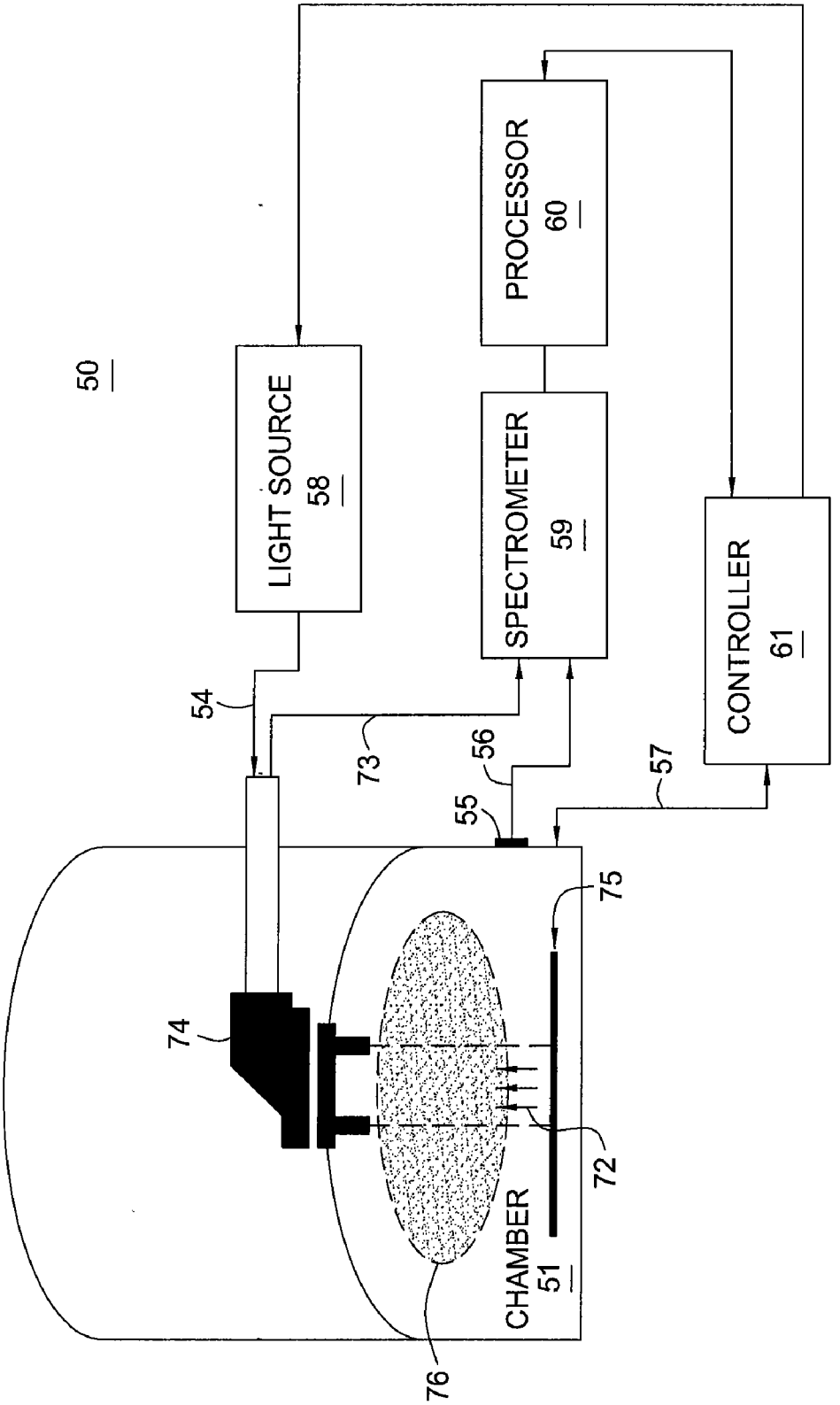

50
LIGHT SOURCE
58
PROCESSOR
60
SPECTROMETER
59
CONTROLLER
61
54
73
56
55
57
75
74
72
CHAMBER
51
76

FIG. 1A

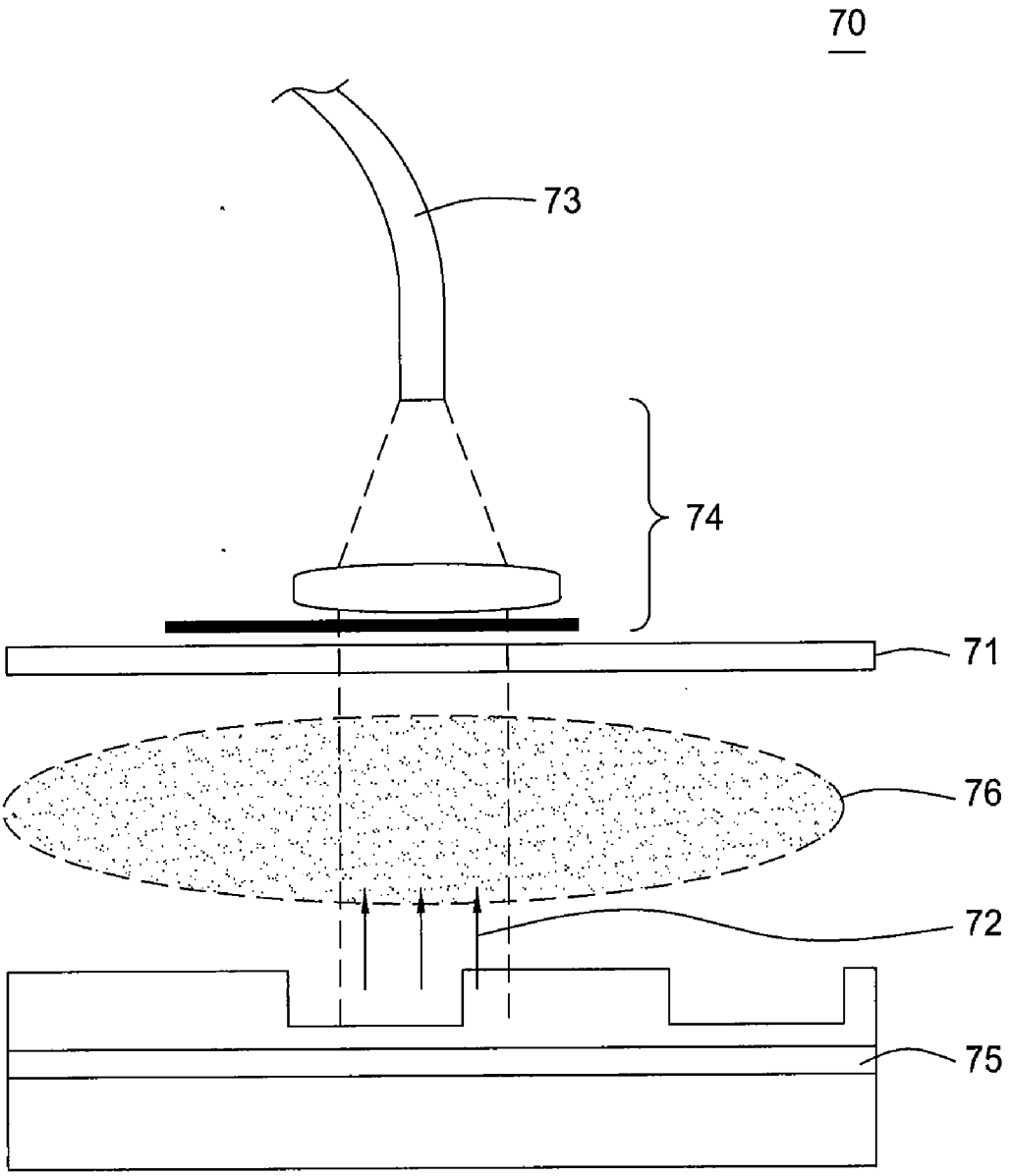


FIG. 1B

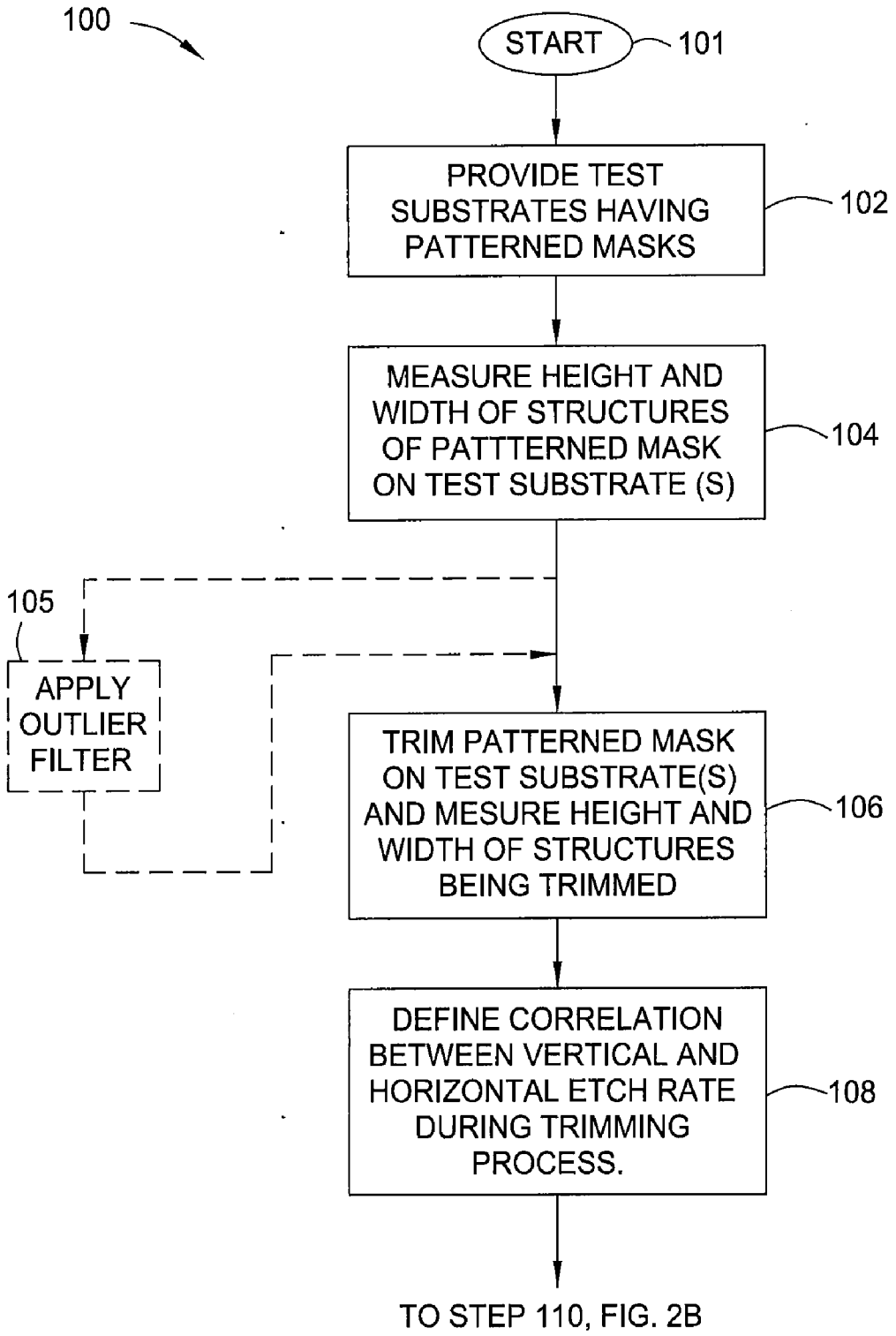

100
START
101
PROVIDE TEST SUBSTRATES HAVING PATTERNED MASKS
102
MEASURE HEIGHT AND WIDTH OF STRUCTURES OF PATTTERNED MASK ON TEST SUBSTRATE (S)
104
105
APPLY OUTLIER FILTER
TRIM PATTERNED MASK ON TEST SUBSTRATE(S) AND MESURE HEIGHT AND WIDTH OF STRUCTURES BEING TRIMMED
106
DEFINE CORRELATION BETWEEN VERTICAL AND HORIZONTAL ETCH RATE DURING TRIMMING PROCESS.
108
TO STEP 110, FIG. 2B

FIG. 2A

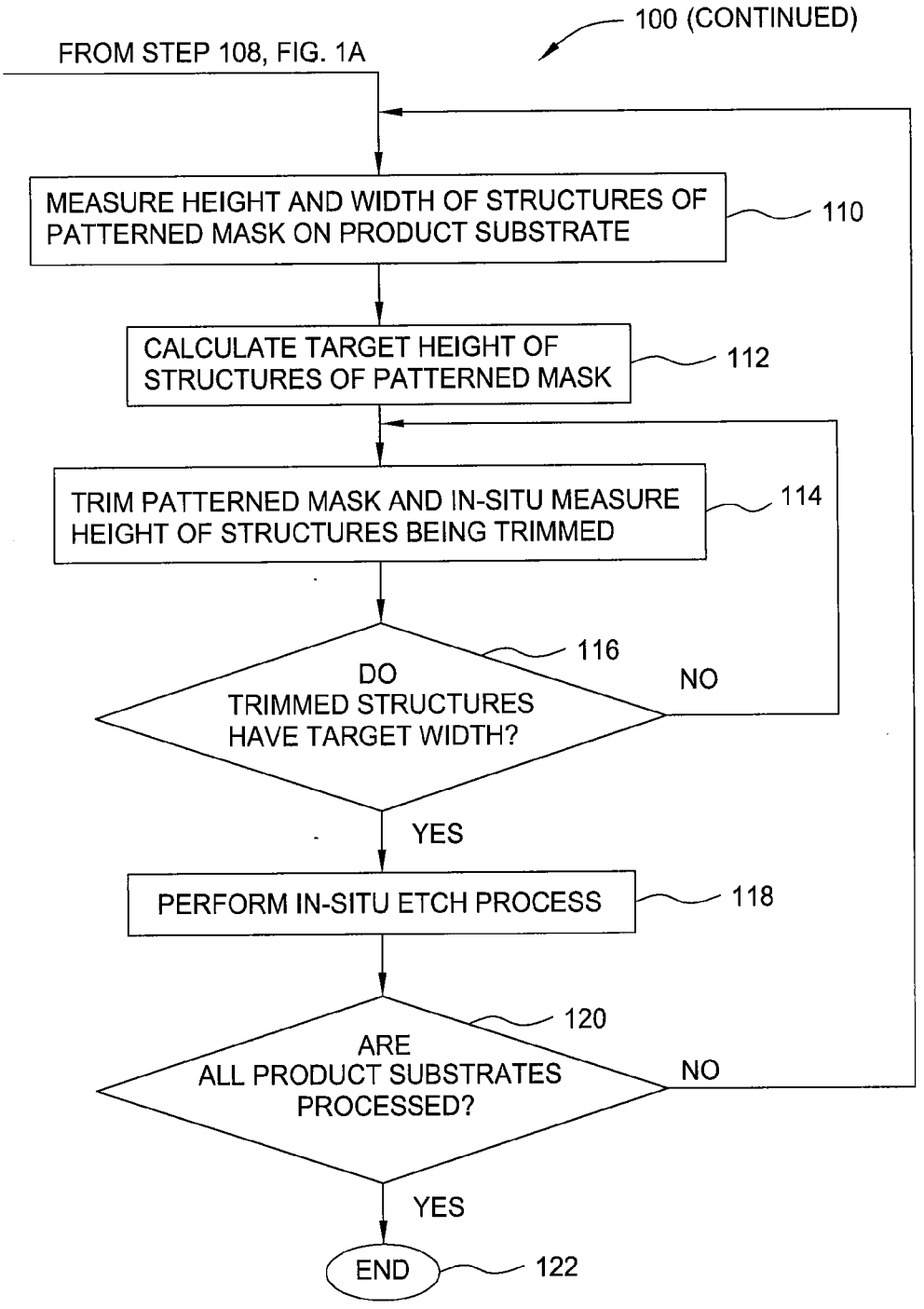

100 (CONTINUED)
FROM STEP 108, FIG. 1A
MEASURE HEIGHT AND WIDTH OF STRUCTURES OF PATTERNED MASK ON PRODUCT SUBSTRATE
110
CALCULATE TARGET HEIGHT OF STRUCTURES OF PATTERNED MASK
112
TRIM PATTERNED MASK AND IN-SITU MEASURE HEIGHT OF STRUCTURES BEING TRIMMED
114
DO TRIMMED STRUCTURES HAVE TARGET WIDTH?
116
NO
YES
PERFORM IN-SITU ETCH PROCESS
118
ARE ALL PRODUCT SUBSTRATES PROCESSED?
120
NO
YES
END
122

FIG. 2B

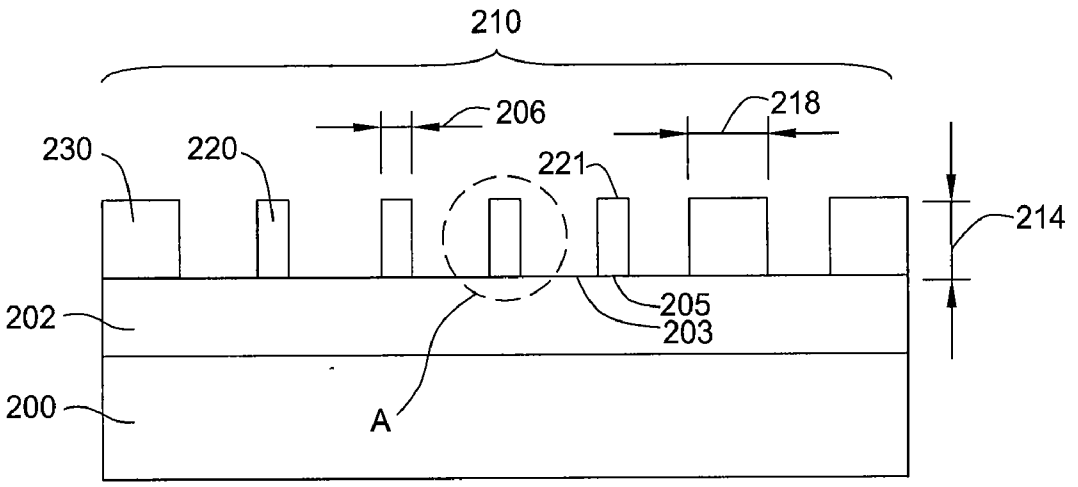

210
206
218
230
220
221
214
205
203
202
200
A

FIG. 3A

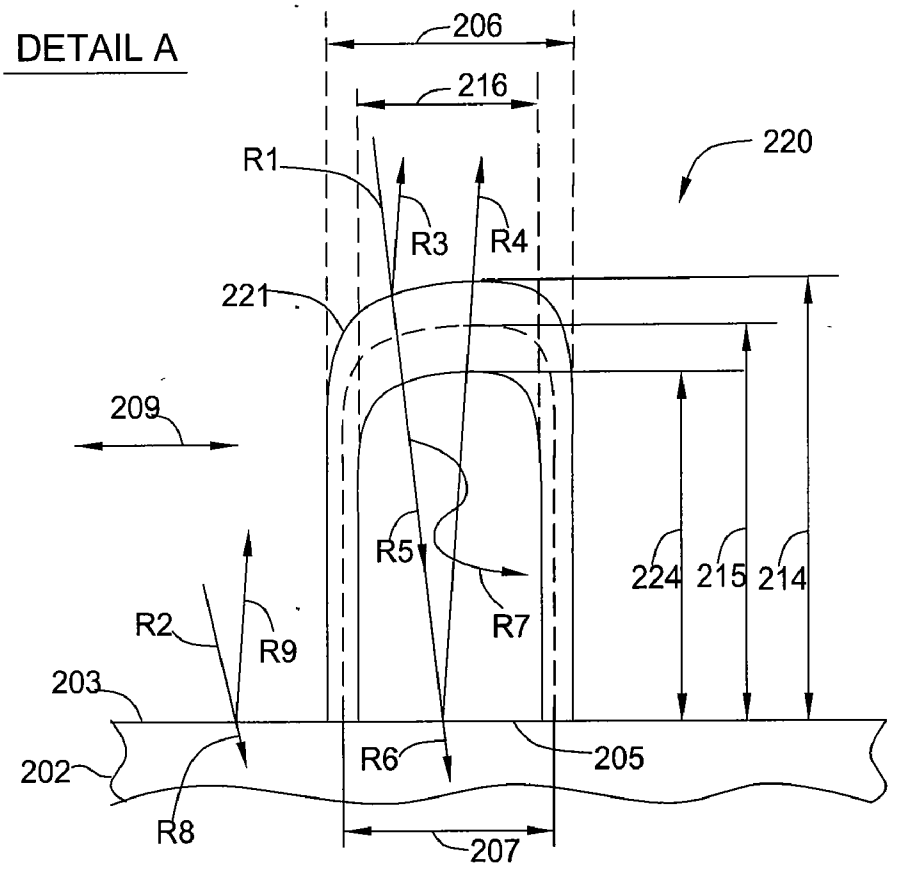

DETAIL A
206
216
220
R1
R3
R4
221
209
R5
224
215
214
R2
R9
R7
203
R6
205
202
R8
207

FIG. 3B

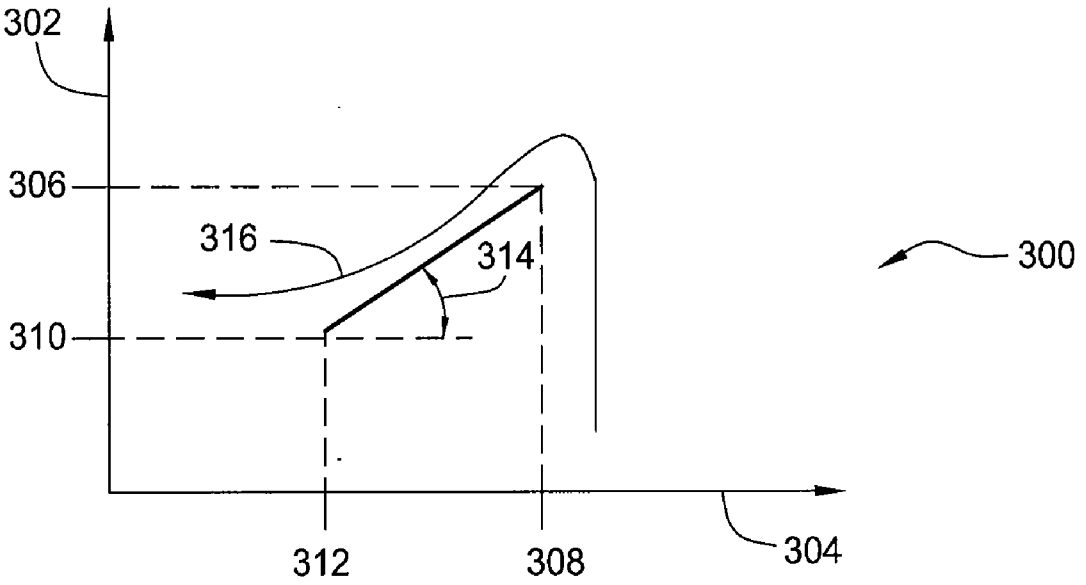


FIG. 4

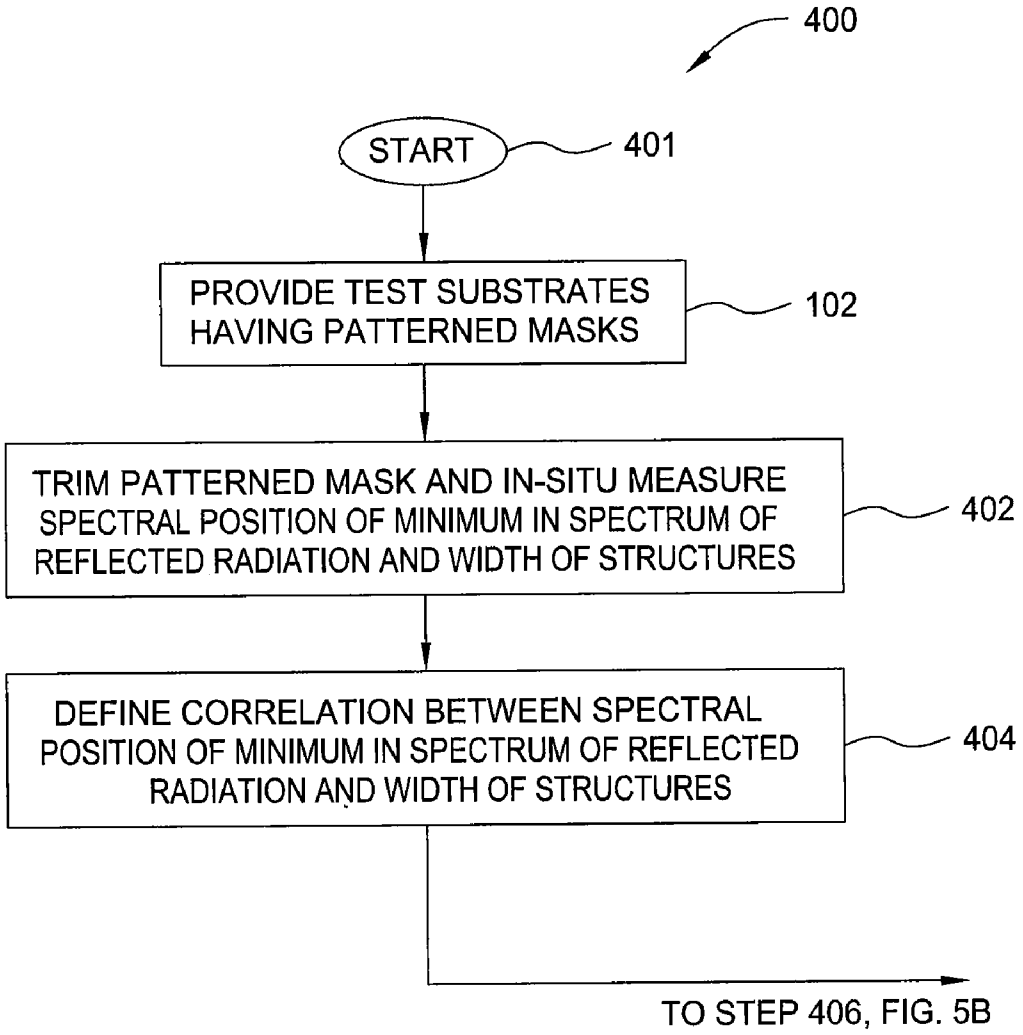

400
START
401
PROVIDE TEST SUBSTRATES HAVING PATTERNED MASKS
102
TRIM PATTERNED MASK AND IN-SITU MEASURE SPECTRAL POSITION OF MINIMUM IN SPECTRUM OF REFLECTED RADIATION AND WIDTH OF STRUCTURES
402
DEFINE CORRELATION BETWEEN SPECTRAL POSITION OF MINIMUM IN SPECTRUM OF REFLECTED RADIATION AND WIDTH OF STRUCTURES
404
TO STEP 406, FIG. 5B

FIG. 5A

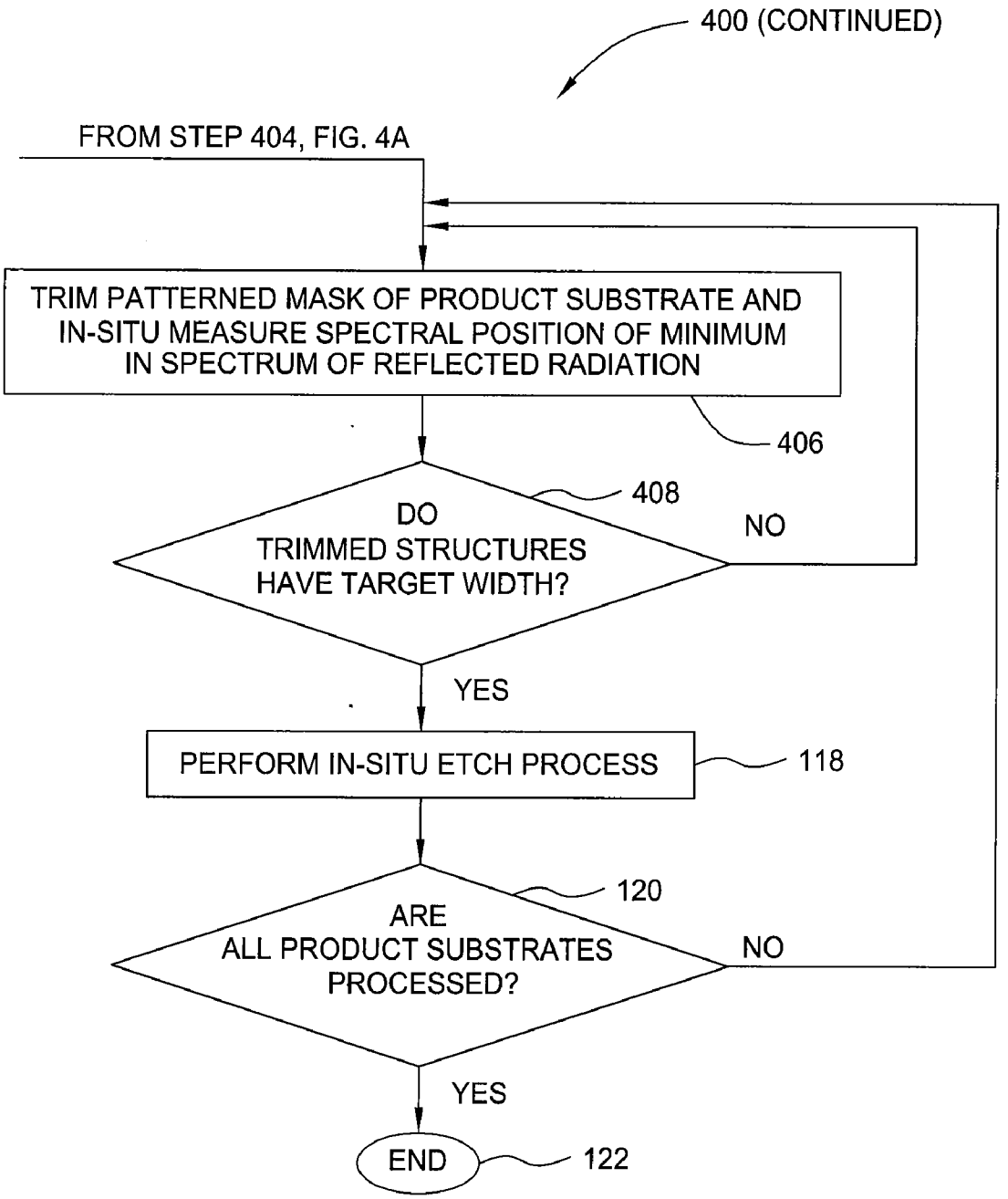

400 (CONTINUED)
FROM STEP 404, FIG. 4A
TRIM PATTERNED MASK OF PRODUCT SUBSTRATE AND IN-SITU MEASURE SPECTRAL POSITION OF MINIMUM IN SPECTRUM OF REFLECTED RADIATION
406
408
DO TRIMMED STRUCTURES HAVE TARGET WIDTH?
NO
YES
PERFORM IN-SITU ETCH PROCESS
118
120
ARE ALL PRODUCT SUBSTRATES PROCESSED?
NO
YES
END
122

FIG. 5B

FIG. 6A

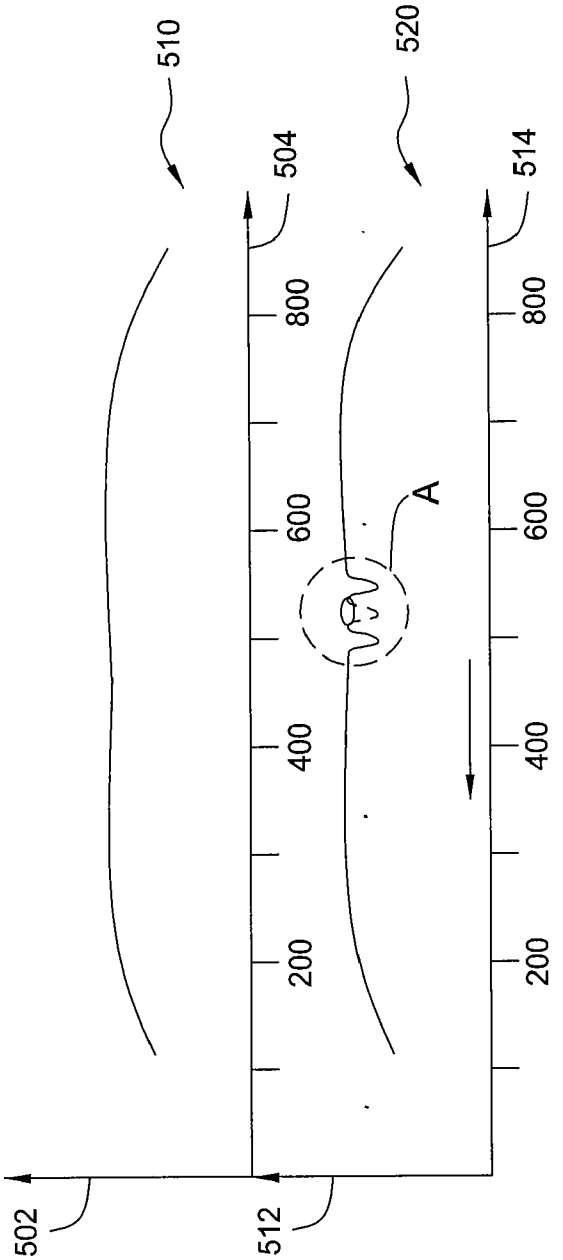
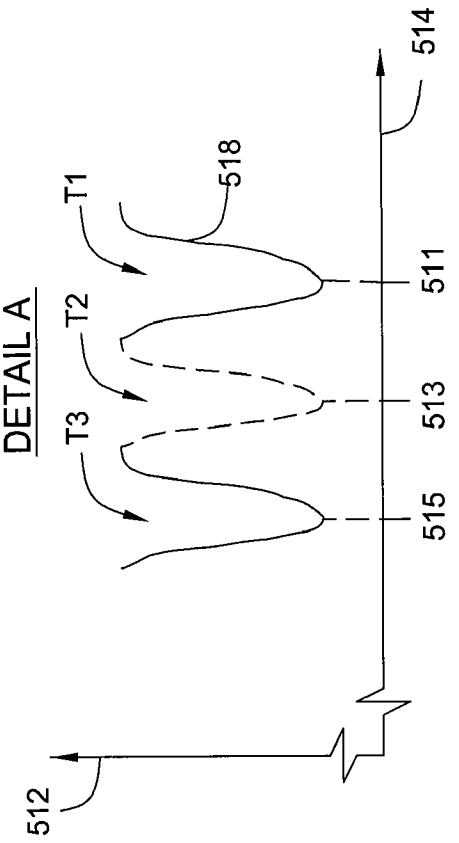

510
520
504
514
800
600
400
200
A
502
512

FIG. 6B


DETAIL A
T1
T2
T3
518
514
511
513
515
512

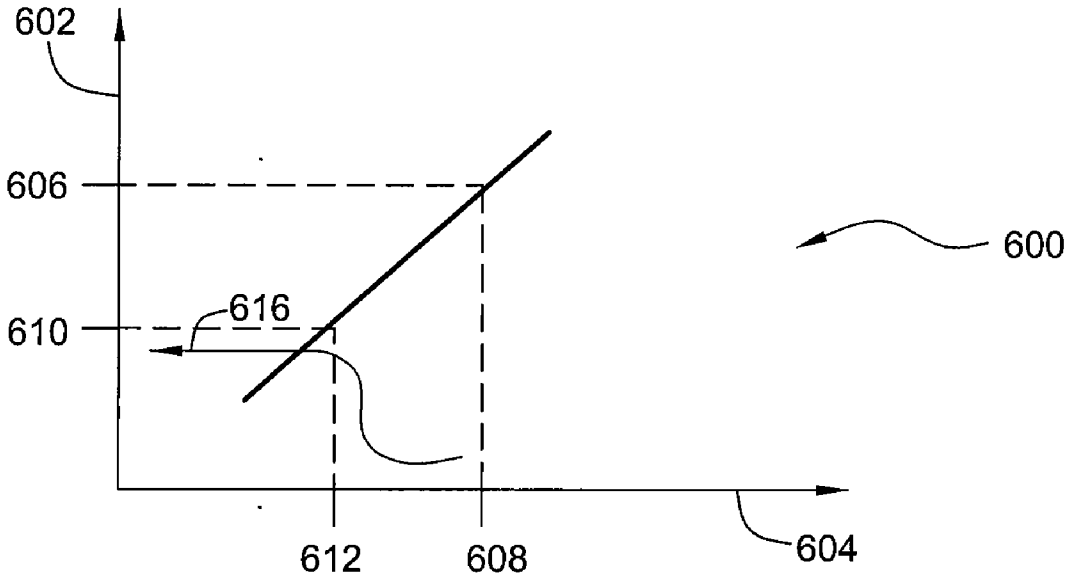


FIG. 7

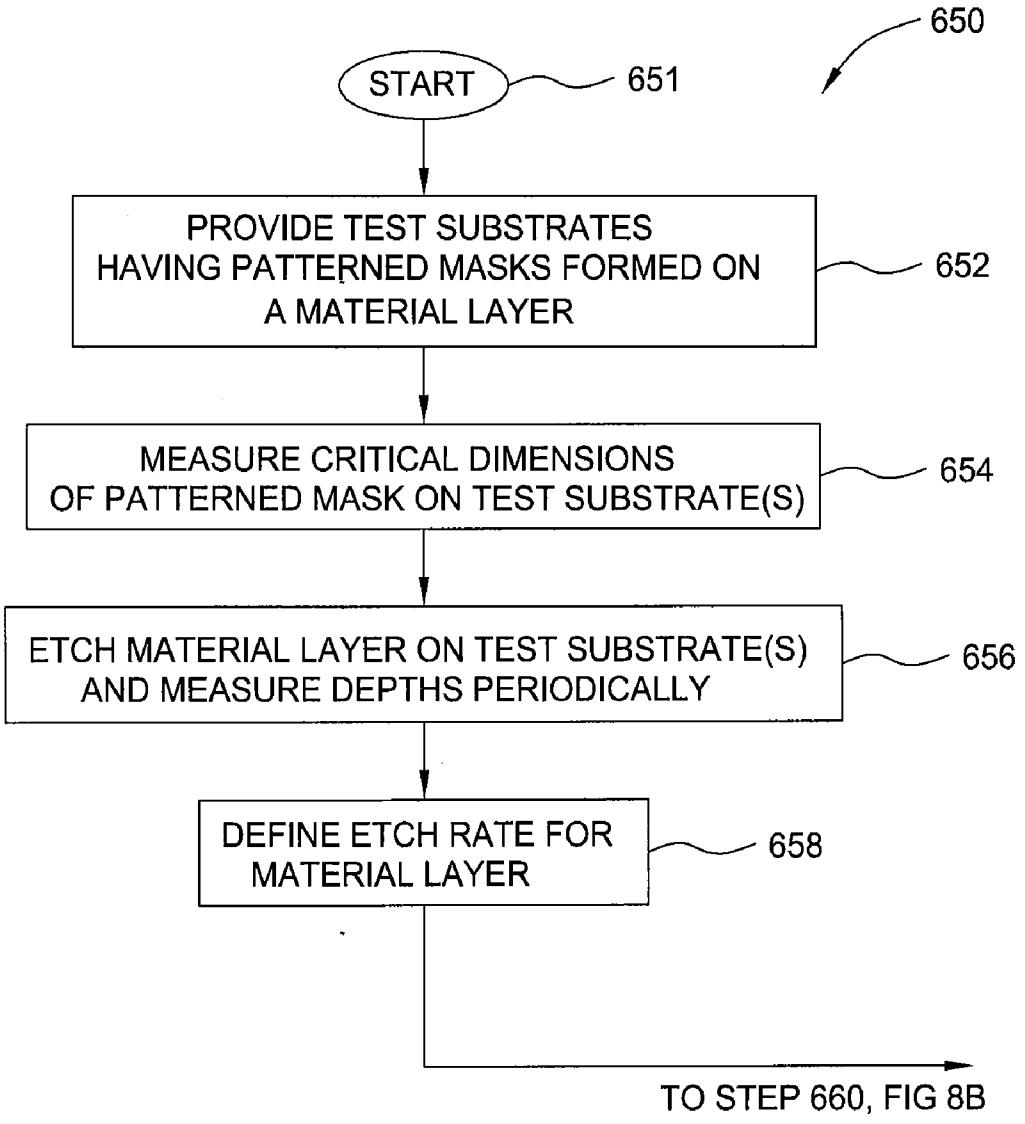

650
START
651
PROVIDE TEST SUBSTRATES HAVING PATTERNED MASKS FORMED ON A MATERIAL LAYER
652
MEASURE CRITICAL DIMENSIONS OF PATTERNED MASK ON TEST SUBSTRATE(S)
654
ETCH MATERIAL LAYER ON TEST SUBSTRATE(S) AND MEASURE DEPTHS PERIODICALLY
656
DEFINE ETCH RATE FOR MATERIAL LAYER
658
TO STEP 660, FIG 8B

FIG. 8A

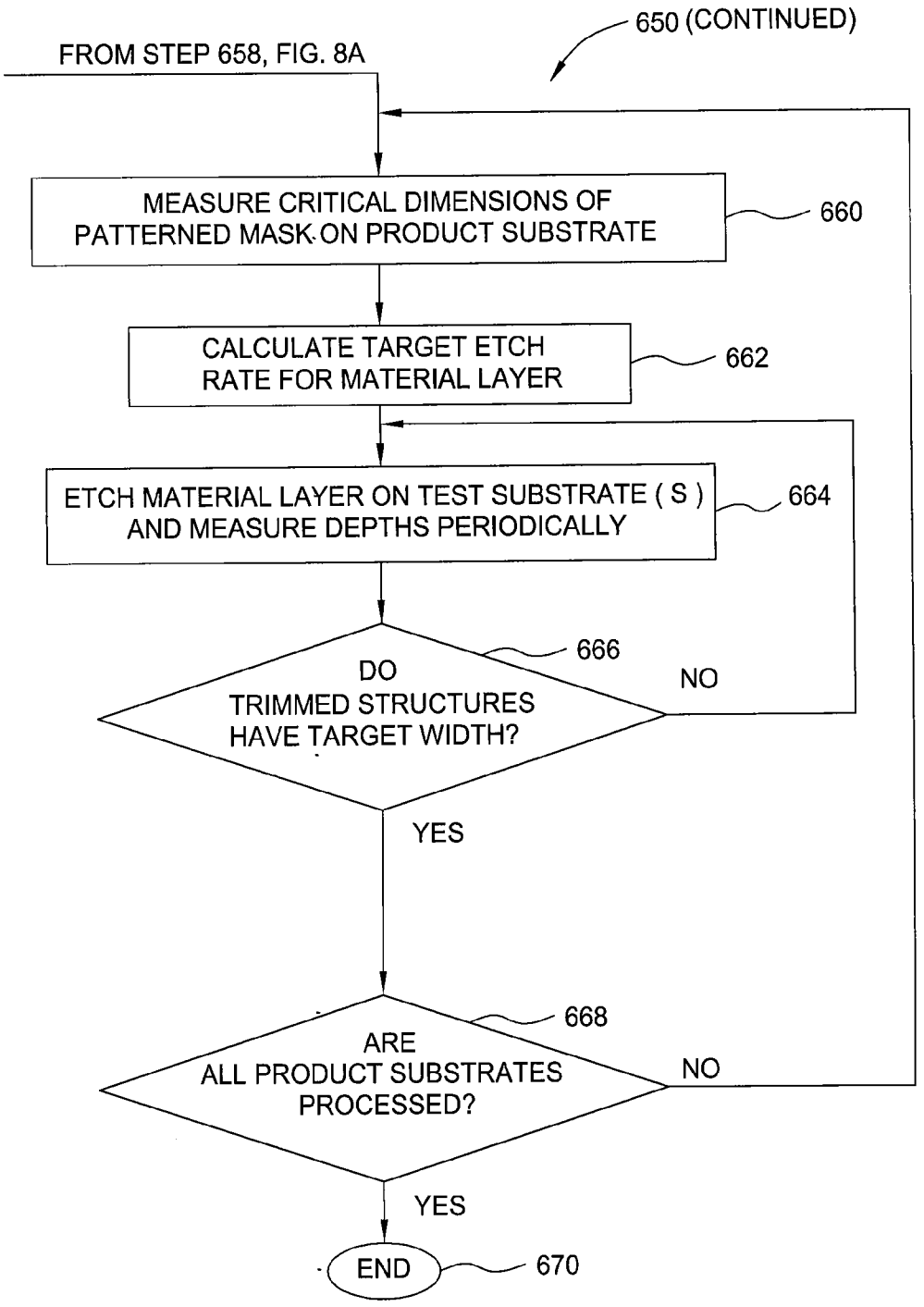

650 (CONTINUED)
FROM STEP 658, FIG. 8A
MEASURE CRITICAL DIMENSIONS OF PATTERNED MASK ON PRODUCT SUBSTRATE
660
CALCULATE TARGET ETCH RATE FOR MATERIAL LAYER
662
ETCH MATERIAL LAYER ON TEST SUBSTRATE (S) AND MEASURE DEPTHS PERIODICALLY
664
666
DO TRIMMED STRUCTURES HAVE TARGET WIDTH?
NO
YES
668
ARE ALL PRODUCT SUBSTRATES PROCESSED?
NO
YES
END
670

FIG. 8B

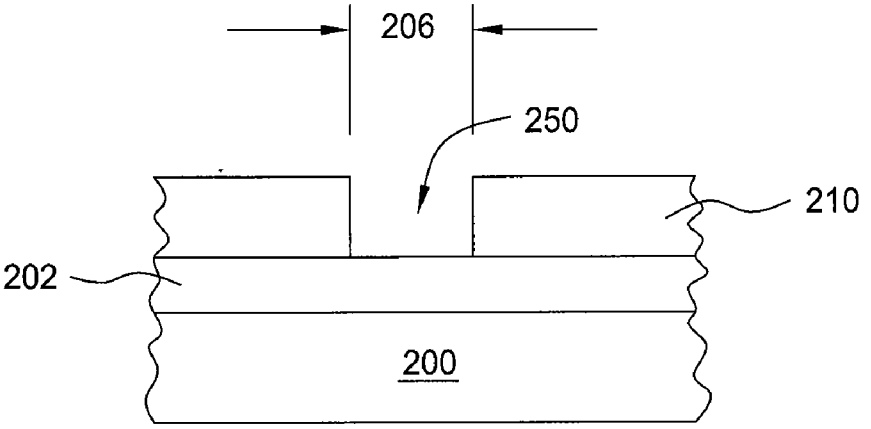


FIG. 9A

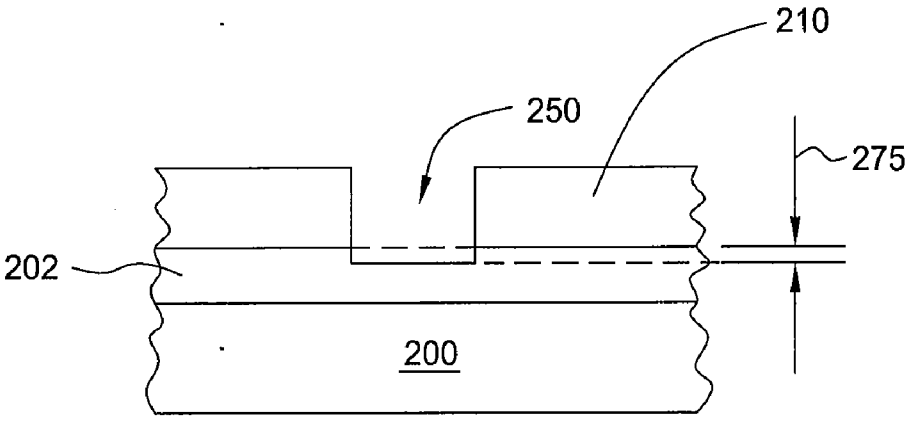


FIG. 9B

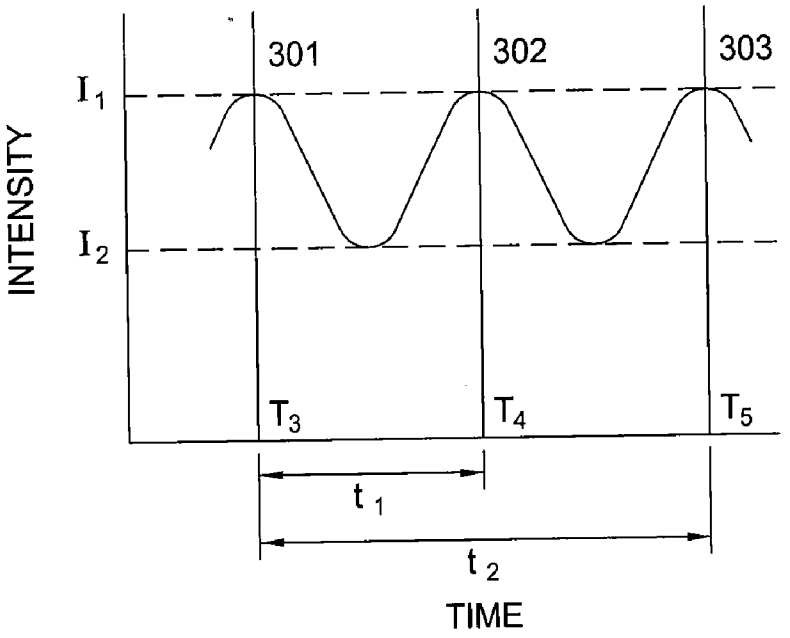

301
302
303
I1
I2
INTENSITY
T3
T4
T5
t1
t2
TIME

FIG. 9C

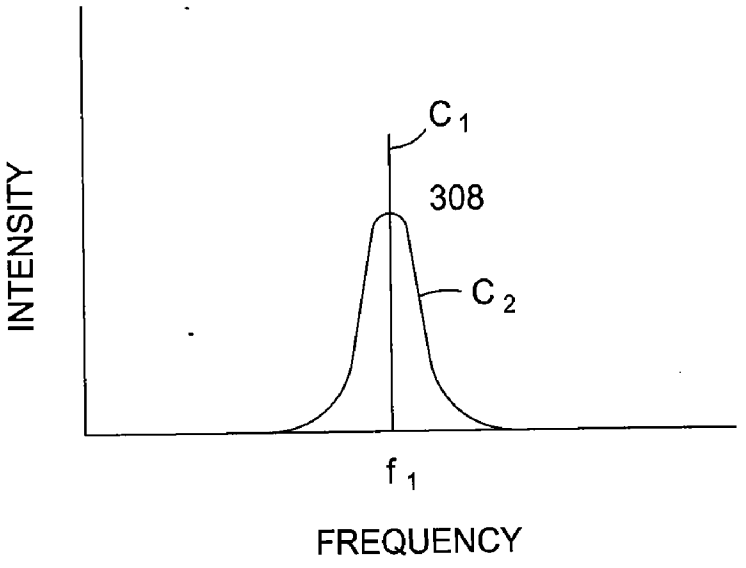

C1
308
C2
INTENSITY
f1
FREQUENCY

FIG. 9D

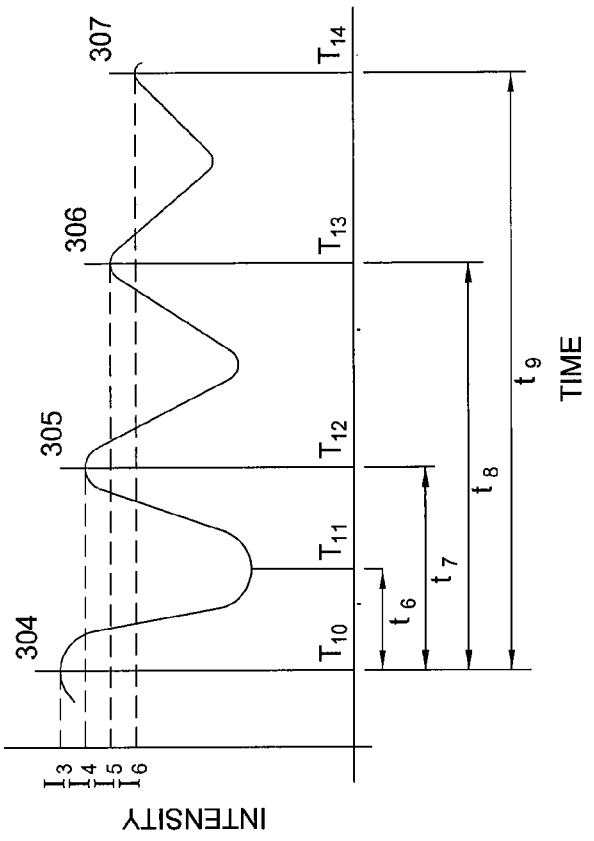


FIG. 9E

FIG. 9F

FIG. 9G

FIG. 9H

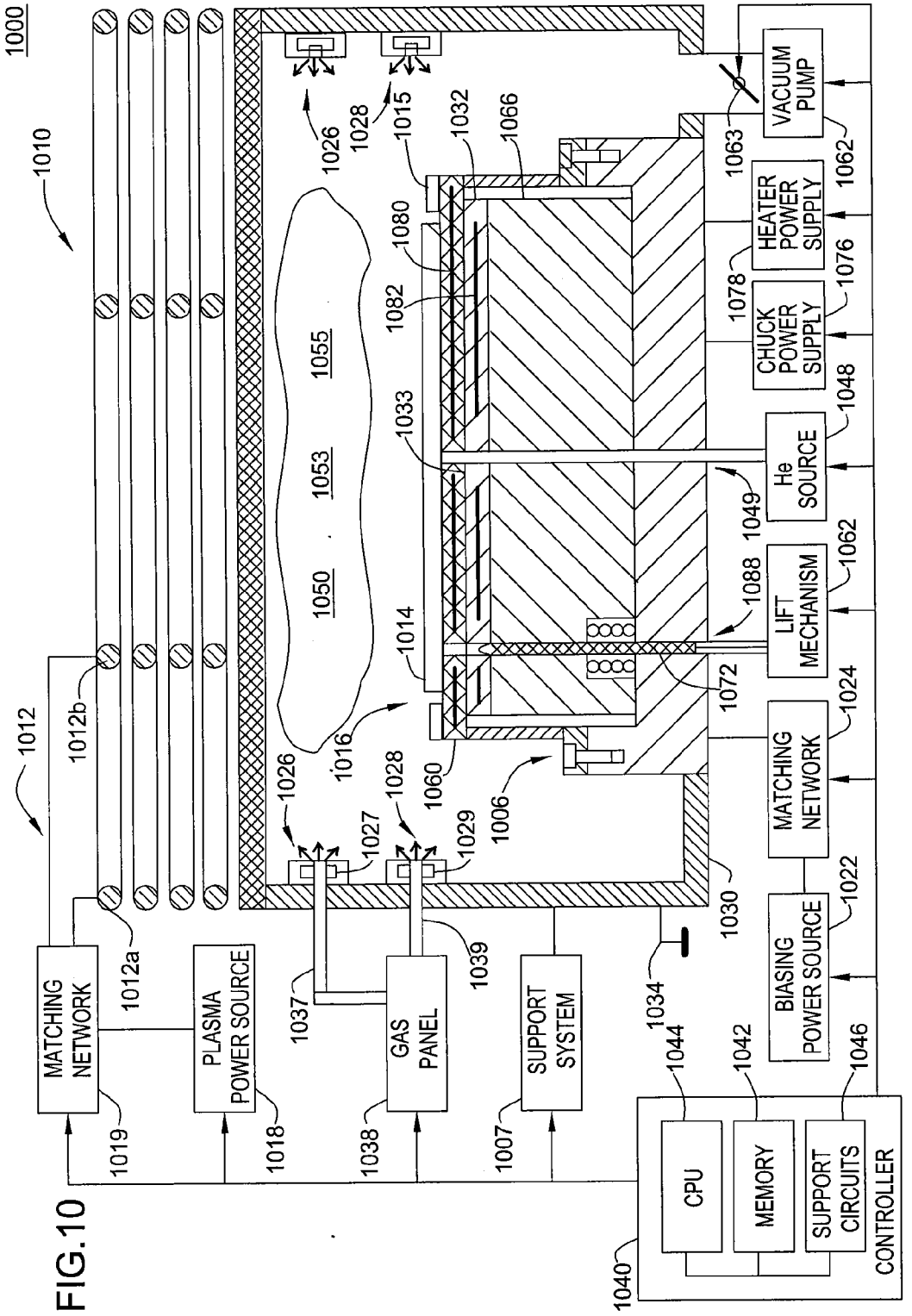

1000
1010
1012
1012a
1012b
1014
1015
1016
1019
1018
1020
1022
1024
1026
1027
1028
1029
1030
1032
1033
1034
1037
1038
1039
1040
1042
1044
1046
1048
1049
1050
1053
1055
1060
1062
1063
1066
1072
1076
1078
1080
1082
1088
MATCHING NETWORK
PLASMA POWER SOURCE
GAS PANEL
SUPPORT SYSTEM
BIASING POWER SOURCE
MATCHING NETWORK
LIFT MECHANISM
He SOURCE
CHUCK POWER SUPPLY
HEATER POWER SUPPLY
VACUUM PUMP
CPU
MEMORY
SUPPORT CIRCUITS
CONTROLLER

FIG.10

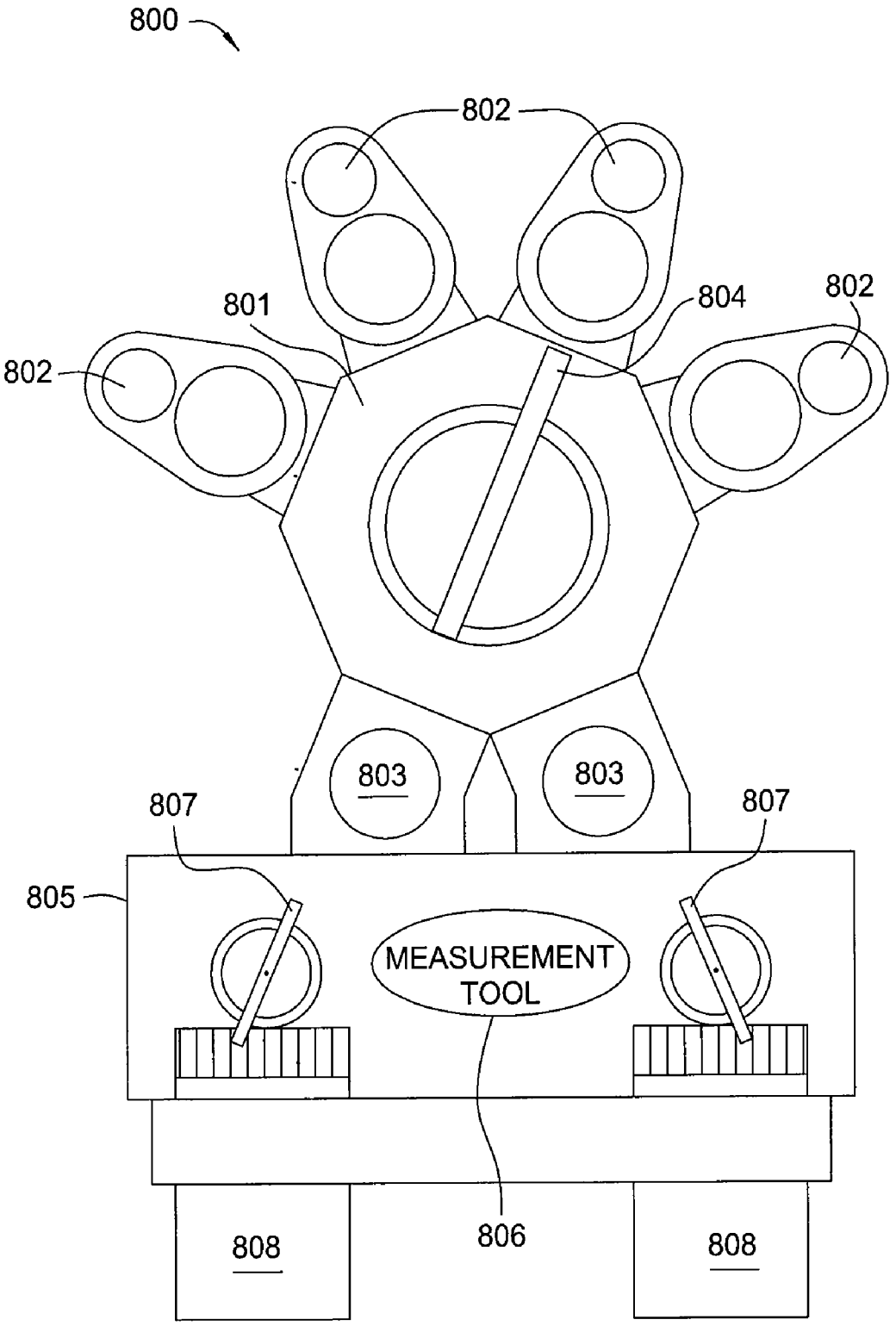

800
802
801
804
802
802
803
803
807
807
805
MEASUREMENT TOOL
806
808
808

FIG. 11

METHOD AND SYSTEM FOR MONITORING AN ETCH PROCESS

CROSS-REFERENCE TO RELATED APPLICATION

[0001] This application is a divisional of U.S. patent application Ser. No. 10/674,568, filed Sep. 29, 2003 (APPM/6716), which claims benefit of U.S. Provisional Application No. 60/479,601 filed Jun. 18, 2003, U.S. Provisional Application No. 60/462,493 filed Apr. 11, 2003 and U.S. Provisional Application No. 60/490,795 filed Jul. 28, 2003, all of which are hereby incorporated by reference in their entireties.

BACKGROUND OF THE INVENTION

[0002] 1. Field of the Invention

[0003] The present invention generally relates to semiconductor substrate processing systems. More specifically, the present invention relates to a method and apparatus for monitoring an etch process.

[0004] 2. Description of the Related Art

[0005] To increase operational speed, devices (e.g., transistors, capacitors, and the like) in integrated microelectronic circuits have become ever smaller. One method of fabricating such devices comprises forming a patterned mask (e.g., photoresist mask) on a material layer formed on a substrate and then etching the material layer using the patterned mask as an etch mask. The etch mask generally is a replica of the structure being formed (i.e., etched) in the underlying material layer (or layers). As such the etch mask has the same topographic dimensions as the structures to be formed in the underlying layer(s).

[0006] Typically, the smallest widths for elements of an etch mask, such as lines, columns, openings, spaces between lines, and the like are measured. Such smallest widths are known as "critical dimensions", or CDs. In advanced ultra large scale integrated (ULSI) circuits, the critical dimensions are generally sub-micron dimensions of about 20 to 200 nm. Additionally, thickness measurements for material layers to be etched are ascertained. Parameters for an etch process recipe are generally selected using statistically generated results of the critical dimension measurements of the patterned masks formed on wafers as well as the thickness measurements of material layers to be etched.

[0007] Accurate etch process monitoring is critical when etching a material layer using a patterned mask. In particular, manufacturing variables for the etch process may decrease dimensional accuracy of devices formed therewith, as well as cause a broad statistical distribution (i.e., a large σ, where is σ a standard deviation) for the dimensions of devices formed on substrates within a group (i.e., batch) of substrates.

[0008] Therefore, there is a need in the art for improved etch process monitoring in the fabrication of integrated circuits.

SUMMARY OF THE INVENTION

[0009] The present invention is a method and system for monitoring an etch process. The etch process may be monitored using measurement information (e.g., critical dimensions (CD), layer thickness, and the like) provided ex-situ with respect to the etch process in combination with in-situ monitoring (e.g., spectroscopy, interferometry, scatterometry, reflectometry, and the like) performed during the etch process. The ex-situ measurement information in combination with the in-situ monitoring may be used to monitor for example, an endpoint of an etch process, an etch depth profile of a feature formed on a substrate, fault detection of an integrated circuit manufacturing process, and the like.

[0010] The ex-situ measurement information is performed prior to and/or after the etch process. The ex-situ measurement information is provided to an etch reactor and is used during the etch process in combination with the in-situ monitoring. The ex-situ measurements may be performed using measurement equipment integrated with the etch reactor (e.g., modules of the same etching system) or alternatively provided from measurement equipment not integrated with the etch reactor (e.g., stand alone equipment). The in-situ monitoring may be performed using measurement equipment coupled to the etch reactor.

BRIEF DESCRIPTION OF THE DRAWINGS

[0011] The teachings of the present invention can be readily understood by considering the following detailed description in conjunction with the accompanying drawings, in which:

[0012] FIG. **1** depicts a flow diagram of a method for monitoring an etch process according to the present invention;

[0013] FIG. **1**A depicts an in-situ metrology tool with interferometric and/or spectrometric measurement assembly and an optical electromagnetic emission (OES) monitoring assembly;

[0014] FIG. **1**B is a schematic diagram of a process chamber showing a path for reflected light from a wafer inside the process chamber to a light collecting devices;

[0015] FIGS. **2**A-**2**B depict a flow diagram of a method for monitoring a mask trimming process in accordance with one embodiment of the present invention;

[0016] FIGS. **3**A-**3**B depict schematic, cross-sectional views of a substrate having a patterned mask being trimmed;

[0017] FIG. **4** shows a graph illustrating the correlation between vertical and horizontal etch rates during a mask trimming process;

[0018] FIGS. **5**A-**5**B depict a flow diagram of a method monitoring a mask trimming process in accordance with another embodiment of the present invention;

[0019] FIGS. **6**A-**6**B depict a series of graphs illustrating changes in the spectral intensity of radiation reflected from a substrate during a mask trimming process;

[0020] FIG. **7** shows a graph illustrating the correlation between the spectral position of a minimum in the spectrum of reflected radiation and the width of the trimmed patterned mask features;

[0021] FIGS. **8**A-**8**B depict a flow diagram of a method of monitoring a material layer etch process in accordance with another embodiment of the present invention;

[0022] FIGS. **9**A-**9**B depict a series of schematic, cross-sectional views of a substrate having a material layer being etched;

[0023] FIG. **9**C depicts a graph of an interference fringe intensity versus time during steady intensity period;

[0024] FIG. **9**D depicts a graph of an interference fringe intensity versus frequency;

[0025] FIG. **9**E depicts a graph of an interference fringe intensity versus frequency during decreasing intensity periods;

[0026] FIG. **9**F depicts a graph of the interference fringe intensity versus frequency between times T_{10} to T_{11} of FIG. **9**E;

[0027] FIG. **9**G depicts a graph of the interference fringe intensity versus frequency between times T_{10} to T_{12} of FIG. **9**E;

[0028] FIG. **9**H depicts a graph of the interference fringe intensity versus frequency between times T_{10} to T_{13} of FIG. **9**E;

[0029] FIG. **10** depicts a schematic view of an exemplary etch reactor including an in-situ monitoring module of the kind used in performing portions of the invention; and

[0030] FIG. **11** depicts a schematic diagram of an exemplary process system of the kind used in performing portions of the invention.

[0031] To facilitate understanding, identical reference numerals have been used, where possible, to designate identical elements that are common to the figures.

[0032] It is to be noted, however, that the appended drawings illustrate only exemplary embodiments of this invention and are therefore not to be considered limiting of its scope, for the invention may admit to other equally effective embodiments.

DETAILED DESCRIPTION

[0033] The present invention is a method and system for monitoring an etch process. The etch process is monitored using measurement information (e.g., critical dimensions (CD), layer thickness, and the like) provided ex-situ with respect to the etch process in combination with in-situ monitoring (e.g., spectroscopy, interferometry, scatterometry, reflectometry, and the like) performed during the etch process. The ex-situ measurement information in combination with the in-situ monitoring may be used to monitor for example, an endpoint of an etch process, an etch depth profile of a feature formed on a substrate, fault detection of an integrated circuit manufacturing process, and the like. Fault detection of an integrated circuit manufacturing process may include for example, monitoring the etch process to determine when the critical dimensions (CD) of features being etched are outside of a pre-determined range so as to halt such process.

[0034] Ex-situ measurement information is performed prior to and/or after the etch process. The ex-situ measurement information is provided to an etch reactor and is used during the etch process in combination with the in-situ monitoring. The ex-situ measurements may be performed using measurement equipment integrated with the etch reactor (e.g., modules of the same etching system) or alternatively provided from measurement equipment not integrated with the etch reactor (e.g., stand alone equipment). The in-situ monitoring may be performed using measurement equipment coupled to the etch reactor.

[0035] FIG. **1** depicts a flow diagram of the inventive method for monitoring an etch process as sequence **10**. The sequence **10** includes a series of processing steps, which may be performed on test and product substrates to accomplish the method.

[0036] The sequence **10** starts at step **11** and proceeds to step **12**. At step **12**, measurement information is provided ex-situ to the etch process. In one embodiment, the ex-situ measurement information comprises critical dimension (CD) information, i.e., the width of the structures, as well as the height of for example a patterned mask. The ex-situ measurement information is generally provided for each substrate of a batch of the substrates. Such ex-situ measurements may be performed using measurement equipment integrated with the etch reactor (e.g., modules of the same etching system) or alternatively provided from measurement equipment not integrated with the etch reactor (e.g., stand alone equipment).

[0037] In one exemplary embodiment, such ex-situ measurement information is determined using a TRANSFORMA™ metrology module of the CENTURA® processing system, available from Applied Materials of Santa Clara, Calif. The TRANSFORMA™ metrology module may use one or more non-destructive optical measuring techniques, such as spectroscopy, interferometry, scatterometry, reflectometry, ellipsometry, and the like. The measured parameters include topographic dimensions and profiles of the structures fabricated on substrates, as well as a thickness of either patterned or blanket dielectric and conductive films. Measurements for critical dimensions of the structures are typically performed in a plurality of regions of the substrate, such as a statistically significant number of regions (e.g., 5 to 9 or more regions), and then averaged for such a substrate.

[0038] Alternatively, the measurement information may be provided to the etch reactor from measurement equipment (e.g., stand alone equipment) not integrated with the etch reactor. Such stand-alone equipment may provide measurement information using scanning electron microscopy (SEM), atomic force metrology (AFM), optical metrology, surface profiling, and the like.

[0039] The ex-situ measurement information may include information related to the topographic dimensions and profiles of the structures to be fabricated. In addition, film thicknesses of either blanket or patterned films (e.g., dielectric films and conductive films) may be provided along with mapping information (e.g., location on a substrate) with respect to film thickness uniformity across topographic structures formed on the substrate.

[0040] Since the ex-situ measurements are used to set the parameters of a subsequent process, any anomalies in the measured data can cause the process parameters to be incorrectly established, resulting in incorrectly processed substrates. The anomalies could be a result of poor photoresist patterning or measurement errors due to local wafer surface condition or defect. To avoid having the process parameters established using incorrect measurement data, an optional outlier filter can be used to remove from the data set any ex-situ data measurements that are not correct. At step **13** (shown in phantom to indicate that this step is optional), an outlier filter is applied to the ex-situ measurement data to remove any data points that are outliers. The outlier filter can also examine the measurement results, such as means, maximum, minimum, standard deviations, goodness of fits and the likes, to determine if the substrate has received good photoresist patterning. Step **14** queries if the substrate passes the "good" patterning criteria, the substrate should receive etch process as described in step **15**. If the results do not pass the "good" patterning criteria at step **14**, the substrate will not receive etch process and will be marked by the system for remeasurement, re-examination or rework.

[0041] At step **15**, the etch process is performed. The etch reactor within which the etch process is performed includes an in-situ monitoring apparatus configured to measure, in real time, metrics associated with the etch process. Performing in-situ real time monitoring during the etch process enhances the determination of, for example, the endpoint for such etch process independent of the etch rate. Additionally, such in-situ monitoring may provide fault detection determination with respect to the etch process (e.g., non-uniformities within

the etch process outside of a predetermined range) as well as provide specific critical dimension information with respect to elements identified using ex-situ mapping of the substrate.

[0042] In one exemplary embodiment, the in-situ metrology tool may be the EyeD™ metrology module, available from Applied Materials of Santa Clara, Calif. As shown in FIG. **1**A, EyeD™ chamber module **50** comprises of two parts. One is an interferometric and/or spectrometric measurement assembly to measure the film thickness and/or the width of structures. The other is an optical electromagnetic emission (OES) monitor assembly to monitor the chamber plasma state.

[0043] The interferometric and/or spectrometric measurement assembly may be, for example, configured to perform an interferometric monitoring technique (e.g., counting interference fringes in the time domain, measuring position of the fringes in the frequency domain, and the like) to measure the etch depth profile of the structures being formed on the substrate in real time. Light **72** reflected from a wafer **75** are collected by beam-forming optics **74** and the signals are transmitted by a signal cable **73** to a spectrometer **59**. The signals are analyzed by the spectrometer **59** and a processor **60**. The analyzed results can be used to generate control commands that control the reactor chamber via controller **61**. If the assembly is used to control the endpoint of an etch process, it is called "interferometric endpoint" (IEP). External light from broadband light source **58**, e.g., a mercury, deuterium or xenon lamp, could be employed to provide light through fiber optic cable **54** to the wafer. Such a light source may be used in addition to or instead of using the plasma as the light source. Details of film thickness measurement and control (or endpoint) by EyeD™ have been disclosed in commonly assigned U.S. Pat. No. 6,413,867, entitled "Film Thickness Control Using Spectral Interferometry", issued on Jul. 2, 2002, and U.S. application Ser. No. 10/286,402 entitled "Interferometric Endpoint Determination In A Substrate Etching Process", filed Nov. 1, 2002. The assembly may also use one or more non-destructive optical measuring techniques, such as spectroscopy, scatterometry, reflectometry, and the like, to measure the width of structures. As shown in FIG. **1**B, light **72** reflected from the wafer **75** surfaces and interfaces passes through a window **71** and is collected by beam-forming optics **74** and signal cable **73**. The signals are analyzed by a spectrometer **59** and a processor **60** (FIG. **1**A) to determine the width of the structures. Details of how to determine the width of the structures will be described below. The images in FIGS. **1**A-**1**B are not depicted to scale and are simplified for illustrative purposes. To best understand the invention, the reader should simultaneously refer to FIGS. **3**A and **3**B.

[0044] Another EyeD™ chamber module is an optical electromagnetic emission (OES) monitor assembly to monitor the chamber plasma state. The OES monitor can be used to determine the degree of chamber matching and the source(s) of process and/or system fault. OES signals emitted from the plasma **76** are collected by a signal collecting device **55** and the signals are transmitted by a signal cable **56**. The signals are analyzed by the spectrometer **59** and the processor **60**. The analyzed results can be used to generate control command and be used to control the reactor chamber via controller **61**. Details of this application have been disclosed in commonly assigned patent application Ser. No. 10/628,001, entitled "Method For Automatic Determination Of Semiconductor Plasma Chamber Matching And Source Of Fault By Comprehensive Plasma Monitoring", filed on Jul. 25, 2003.

[0045] At step **16** of FIG. **1**, the sequence **10** queries if all substrates from the batch of such substrates have been processed. If the query of step **16** is negatively answered, the sequence **10** proceeds to step **12**. If the query of step **16** is affirmatively answered, the sequence **10** proceeds to step **18**. At step **18**, the sequence **10** ends.

[0046] In one illustrative etch process, the endpoint of a photoresist trimming process is monitored using ex-situ critical dimension (CD) measurement information in combination with in-situ monitoring performed during the trim process. In one embodiment, the in-situ monitoring uses a metric associated with a correlation between a vertical etch rate and a horizontal etch rate of the trimming process. In another embodiment, the in-situ monitoring uses a metric associated with a correlation between a spectral position of a minimum in the spectrum of radiation reflected from the substrate and a width for structures of the patterned mask.

[0047] A process system suitable for facilitating the trimming process includes a metrology module for measuring critical dimension (CD) (e.g., widths) of the structures of the patterned mask and an etch reactor for performing the etch process (e.g., trimming process). The etch reactor includes an in-situ module for monitoring a metric associated with the structures being etched (e.g., spectral intensity of the radiation reflected from the substrate or a correlation between the vertical etch rate and the horizontal etch rate).

[0048] FIGS. **2**A-**2**B depict a flow diagram of one exemplary etch process for monitoring the endpoint of a mask trimming process as a sequence **100**. The sequence **100** includes a series of processing steps, which may be performed on test and product substrates.

[0049] FIGS. **3**A-**3**B depict schematic, cross-sectional views of a substrate having a mask being trimmed using the inventive method. The images in FIGS. **3**A-**3**B are not depicted to scale and are simplified for illustrative purposes. To best understand the invention, the reader should simultaneously refer to FIGS. **2**A-**2**B and FIGS. **3**A-**3**B.

[0050] The sequence **100** starts at step **101** and proceeds to step **102**. At step **102**, a layer **202** and a patterned mask **210** are illustratively formed on a substrate **200** (e.g., silicon wafer) (FIG. **3**A). For convenience, herein the same schematic, cross-sectional view and respective reference numerals may relate to either a test or product substrate **200**.

[0051] The layer **202** may comprise a single material film (e.g., dielectric film, metal film, or any other film used in integrated circuits) or a multi-layered film stack, either unpatterned (as shown) or, alternatively, patterned. During a subsequent etch process, the layer **202** may be etched using the patterned mask **210** as an etch mask. The layer **202** can be formed using any conventional thin film deposition technique, for example, atomic layer deposition (ALD), physical vapor deposition (PVD), chemical vapor deposition (CVD), plasma enhanced CVD (PECVD), and the like that is performed using, e.g., respective processing reactors of CENTURA®, ENDURA®, or other processing systems available from Applied Materials, Inc. of Santa Clara, Calif.

[0052] The patterned mask **210** may generally be in a form of a photoresist mask, an α-carbon (i.e., amorphous carbon) mask, a hard mask, an Advanced Patterning Film™ (APF) available from Applied Materials of Santa Clara, Calif., and the like. In one exemplary embodiment, the patterned mask **210** is a photoresist mask. Illustratively, referring to FIG. **3**A,

the patterned mask **210** has a height **214** and includes structures **220** and **230** (e.g., lines, walls, columns, and the like) having widths **206** and **218**, respectively. The width **206** is smaller than the width **218** or a width of any other structure of the patterned mask **210**. Structures **220** having the smallest widths (i.e., critical dimensions, or CDs) generally are the most difficult structures to fabricate on the patterned mask.

[0053] The photoresist mask **210** may be fabricated using a lithographic process in which a pattern of features of the device to be formed is optically transferred into a layer of photoresist. The photoresist is then developed, unexposed portions of the photoresist are removed, and the remaining photoresist forms the patterned mask **210**. When the patterned mask **210** is a photoresist mask, the layer **202** may further comprise an optional anti-reflective coating (ARC). As sizes of structures of the patterned mask are reduced, inaccuracies in a pattern transfer process may arise from optical limitations inherent to the lithographic process, such as light reflection. The ARC enhances the resolution of the lithographic process by controlling reflection of the light used to expose the photoresist. In one exemplary embodiment, the lithographic process forms the structures **220** having smallest widths **206** of about 80 nm to about 120 nm. Processes of forming the patterned mask **210** are described, for example, in commonly assigned U.S. patent application Ser. No. 10/218,244, filed Aug. 12, 2002 (Attorney docket number 7454), which is incorporated herein by reference.

[0054] At step **104**, the substrate(s) **200** are inspected and topographic dimensions for structures of the patterned mask **210** are measured. In one embodiment, the measured dimensions comprise critical dimensions, i.e., the width **206** of the structures **220**, as well as the height **214** of the patterned mask **210**. The width **206** and height **214** are generally measured on each test substrate **200** of a batch of the test substrates. Such measurements may be performed using a metrology tool that is ex-situ with respect to the etch reactor. In one exemplary embodiment, such optical measuring tool is the TRANSFORMA™ metrology module of the CENTURA® processing system available from Applied Materials of Santa Clara, Calif. The TRANSFORMA™ metrology module may use one or more non-destructive optical measuring techniques, such as spectroscopy, interferometry, scatterometry, reflectometry, ellipsometry, and the like.

[0055] The measured parameters include topographic dimensions and profiles of the structures fabricated on substrates, as well as a thickness of either patterned or blanket dielectric and conductive films. Measurements of critical dimensions for the structures **220** are typically performed in a plurality of regions of the substrate **200**, such as a statistically significant number of the regions (e.g., 5 to 9 or more regions), and then averaged for such a substrate.

[0056] Due to optical limitations of the lithographic process, the photoresist patterned mask **210** typically comprises structures (e.g., structures **220**, **230**, and the like) which are scaled-up images of the features to be etched in the underlying layer(s), e.g., layer **202**. As such, after the lithographic process, the photoresist mask **210** should be trimmed to reduce the widths of such structures before the mask may be used as the etch mask.

[0057] At step **105**, an outlier filter may be optionally applied to the height and width values such that those data points that are outliers are removed from the data set. Such outliers are caused by poor local wafer surface conditions or defects. If not removed, outliers may result in the substrate processing parameters being incorrectly established.

[0058] At step **106**, the patterned mask **210** is trimmed to reduce the widths of the structures **220** and **230** to pre-determined values. As illustratively shown in FIG. **3**B, step **106** trims the structures **220** to a pre-determined width **216**. Simultaneously, step **106** reduces the width of any other structure (i.e., the width **218** of the structure **230**) of the patterned mask **210** in the same ratio as the width **206** is reduced. A trimming process is generally an isotropic etch process (e.g., isotropic plasma etch process) having a high lateral etch rate and high selectivity for the material of the patterned mask **210** (e.g., photoresist) over the material of the underlying layer **202**. Typically, using the trimming process, widths of the features of the patterned mask **210** (i.e., structures **220**, **230**, and the like) may reduced in a range of about 35 to 80%. By knowing the width and height of the patterned mask **210**, the method establishes a "trim time" during which isotropic etch is performed. The value of the "trim time" establishes the amount of trimming that will occur.

[0059] Step **106** may be performed using an etch reactor, e.g., the Decoupled Plasma Source (DPS II) module of the CENTURA® system. The DPS II module (discussed below in reference to FIG. **10**) uses an inductive source (i.e., antenna) to produce a high-density plasma.

[0060] In one exemplary embodiment, the photoresist mask **210** is trimmed using the DPS II module by providing hydrogen bromide (HBr) at a flow rate of 2 to 200 sccm, oxygen (O_2) at a flow rate of 5 to 100 sccm (e.g., a HBr:O_2 flow ratio ranging from 1:10 to 10:1), argon (Ar) at a flow rate of 10 to 200 sccm, applying power to an inductively coupled antenna between about 200 to 1000 W, applying a cathode bias power between 0 and 300 W, and maintaining a wafer pedestal temperature between 0 and 80 degrees Celsius at a pressure in the process chamber between 2 and 30 mTorr. One illustrative process provides hydrogen bromide (HBr) at a flow rate of 60 sccm, oxygen (O_2) at a flow rate of 28 sccm (i.e., a HBr:O_2 flow ratio of about 2:1), argon (Ar) at a flow rate of 60 sccm, applies 600 W of power to the inductively coupled antenna, 100 W of cathode bias power and maintains a wafer pedestal temperature of 50 degrees Celsius at a pressure of 4 mTorr.

[0061] In one embodiment, the etch reactor further comprises an in-situ metrology tool configured to measure in real time a metric that corresponds to a height of the structures on the substrate being etched (e.g., the height **214** of the structures **220**). During the trimming process, the in-situ metrology tool illuminates the substrate **200** using a broadband radiation source to produce radiation (i.e., incident radiation) having wavelengths in ultra-violet and deep ultra-violet ranges, e.g., from about 200 to 800 nm. Generally, such radiation is directed substantially perpendicular to the substrate **200** and illuminates a region having topographic dimensions of less than about 1 mm. More specifically, the in-situ measuring tool illuminates a region of the substrate **200** that is occupied by the structures (i.e., structures **220**) having critical dimensions, such as the width **206**.

[0062] To increase accuracy of the measurements, the intensity of incident radiation may optionally be modulated and/or pulsed, as well as the radiation may optionally be polarized. The frequency of the incident radiation of modulation is about 10 Hz. The incident radiation may be pulsed using a chopper. In one embodiment, results were obtained using the incident radiation linearly polarized in the direction (shown using arrow **209**) that is approximately orthogonal to

sidewalls of the structures **220**. Generally, the in-situ measuring tool may be configured to perform interferometric and/or spectrometric measurements (discussed below in reference to FIG. **10**). In one exemplary embodiment, such in-situ measuring tool is the EyeD™, available from Applied Materials, Inc. of Santa Clara, Calif.

[0063] The incident radiation (ray R**1**), when radiated by the in-situ measuring tool to illuminate the structure **220**, is partially reflected back (ray R**3**) from a surface **221** and partially propagates (ray R**5**) into the structure **220**. The ray R**5** further partially propagate through a surface **205** beneath the structure into the layer **202** (ray R**6**) and absorbed therein, partially are trapped in (rays R**7**) and absorbed by the material of the structure **220** (e.g., photoresist), and partially are reflected back (ray R**4**). Correspondingly, a portion of the incident radiation (ray R**2**) illuminating regions **203** near the structures **220** may partially propagate into the layer **202** (ray R**8**) where they are absorbed, with a portion reflected back (ray R**9**) from the layer **202**.

[0064] The sequence **100** uses the in-situ measuring tool configured to perform an interferometric measuring technique (e.g., counting interference fringes in the time domain, measuring position of the fringes in the frequency domain, and the like) to measure the height of the structures **220** of the patterned mask **210**. In one specific embodiment, the in-situ measuring tool uses the interference pattern formed by rays R**9**, R**4** and R**3** to measure, during the trimming process, to determine a change of the height **215** of the structures **220** with respect to a pre-selected height (e.g., starting height **214**) of the structures. In these measurements, a portion of the incident radiation may also be used as the reference radiation. In one embodiment, the interferometric measurements are performed using at least one wavelength in the spectrum of the radiation.

[0065] In one exemplary embodiment, the in-situ measuring tool periodically measures in real time an intermediate height (i.e., height **215**) of the structures **220** of patterned mask **210** as the trimming process progresses (for example, measurements performed every 100 milliseconds). The trimming process and measurements continue until the intermediate width **207** becomes equal to or smaller than the pre-determined width **216**. To increase accuracy when measuring the height **215** and width **207**, these measurements may be repeated using several test substrates **200** and then statistically processed (e.g., averaged).

[0066] At step **108**, a correlation between a vertical etch rate and the horizontal etch rate of the trimming process is defined. Such a correlation is defined using the results of measurements performed during step **106**. It has been discovered that, during a trimming process, a horizontal trim (i.e., etch) rate is proportional to the vertical trim rate. As such, any trimming process recipe may be characterized by a related fixed proportion between the horizontal and vertical etch rates. Herein the terms "horizontal trim rate" and "vertical trim rate" relate to a rate of lateral etching the structures of the patterned mask **210** and the rate of decreasing the height of the structures during the trimming process, respectively.

[0067] Referring to FIG. **3**B, the horizontal trim rate specifically relates to the rate of decreasing the width **206** and the vertical trim rate relates to the rate of decreasing the height **214** of the structures **220**. During the trimming process, using the results of in-situ measurements for vertical dimensions (i.e., height **215**) of the structures **220** of the patterned mask **210** being trimmed, the width (i.e., width **207**) of such structures may be calculated. The sequence **100** uses the correlation between a calculated target height **224** and the pre-determined width **216** of the structures **220** having the pre-trimmed height **214** and starting width **206** for close-loop control of an end point of the trimming process. As such, the structures **220** may be controllably trimmed to the pre-determined width **216**.

[0068] At step **110**, a batch of product substrates each having the patterned mask **210** (e.g., photoresist mask) is provided. Prior to the trimming process, the width **206** and height **214** of the structures **220** are measured on each product substrate. In one exemplary embodiment, these measurements are performed using the same measuring tool (e.g., TRANSFORMA™ metrology module) and same methodology as described above in step **104** with reference to the test substrates.

[0069] At step **112**, the target height **224** of the structures **220** is calculated for each product substrate using the defined correlation (step **108**) between the starting width **206** (measured at step **110**) of the structure to be trimmed, vertical trim rate of the trimming process, and the pre-determined (target) width **216** of the trimmed structure.

[0070] At step **114**, the patterned mask **210** of the product substrate is trimmed using an etch rector comprising the in-situ measuring tool adapted to measure, in real time, the height of the structures of the mask **210**. During the trimming process, the in-situ measuring tool in real time measures the intermediate height (i.e., height **215**) of the structures **220** of the patterned mask **210** (e.g., photoresist mask) being trimmed and communicates the results of these measurements to a processor (or controller) of the etch reactor. In one exemplary embodiment, the trimming process is performed using the DPS II module comprising the in-situ measuring tool described above in reference to step **106**.

[0071] At step **116**, the sequence **100** queries if the height (i.e., intermediate height **215**) of the structures **220** has been trimmed to the target height **224** calculated at step **112** above. If the query of step **116** is negatively answered, the sequence **100** proceeds to step **114** to continue the trimming process and real time in-situ measurements of the intermediate height **215** of the structures **220**. If the query of step **116** is affirmatively answered, the sequence **100** proceeds to an optional step **118**.

[0072] At step **118**, the layer **202** may be in-situ etched using the trimmed patterned mask **210** as an etch mask. At step **120**, the sequence **100** queries if all product substrates from the batch of such substrates have been processed. If the query of step **120** is negatively answered, the sequence **100** proceeds to step **110**. If the query of step **120** is affirmatively answered, the sequence **100** proceeds to step **122**. At step **122**, the sequence **100** ends.

[0073] FIG. **4** depicts a graph **300** illustrating exemplary results of the measurements performed on the test substrate **200** during step **106**. More specifically, the graph **300** depicts a width (y-axis **302**) of a structure (e.g., structure **220**) of the patterned mask **210** versus the height (x-axis **304**) of the structure during the trimming process. In the graph **300**, an angle **314** corresponds to a ratio between the horizontal and vertical trim rates. The measurements **308** and **306** relate to the width **206** and height **214** of the structure **220** to be trimmed, respectively. Accordingly, the measurements **312** and **310** correspond to the pre-determined width **216** and the target height **224** of the trimmed structure **220**. Using the

graph **300** (shown for simplicity as a linear graph), at step **108**, the target height **224** may be calculated as illustrated using arrow **316**.

[0074] FIGS. **5**A-**5**B depict a flow diagram of another embodiment of the inventive method for endpoint detection of a mask trimming process as sequence **400**. The sequence **400** includes a series of processing steps, which are performed on test and product substrates to accomplish the method. In FIGS. **2**A-**2**B and FIGS. **5**A-**5**B, the same reference numerals are used to designate similar processing steps. To best understand the invention, the reader should simultaneously refer to FIGS. **5**A-**5**B and FIGS. **3**A-**3**B.

[0075] The sequence **400** starts at step **401**, performs step **102**, and proceeds to step **402**. At step **402**, the test substrate **200** is transported to an etch reactor (e.g., the DPS II module of the CENTURA® system) comprising the in-situ optical measuring tool described above in reference to step **104** of the sequence **100**. The sequence **400** uses the in-situ measuring tool configured to perform spectrometric measurements. Step **402** trims the patterned mask **210** using, e.g., the trimming process described above in reference to step **106**, as well as contemporaneously performs measurements of the spectral intensity of a portion of the radiation reflected from the substrate **200**. Herein the term "spectral intensity" is used to describe distribution of energy of the radiation in the spectrum of the radiation.

[0076] In one embodiment, the in-situ measuring tool performs these measurements using a portion of the radiation that is reflected from the region on the substrate **200** that is occupied by the structures **220**. The trimming process is terminated periodically (for example, every 100 milliseconds) for measuring the intermediate width **207** of the structures **220** being trimmed. These measurements may be performed in-situ using, e.g., the EyeD™ metrology module described above in reference to step **104** of the sequence **100**.

[0077] The spectral intensity of the radiation reflected back from the surfaces **221**, **205** and regions **203** (i.e., rays R**3**, R**4**, and R**9**) does not change noticeably during the trimming process. However, the structure **220** selectively traps in and absorbs the radiation (i.e., ray R**7**) having wavelengths coinciding with the intermediate width **207** of the structure. More specifically, the structure **220** having a width D and formed from material having a coefficient of refraction N, selectively traps in and absorbs the radiation having a wavelength λ_{MIN} that is proportional to λ_D=N×D. It is believed that the trapping of the radiation having the wavelength λ_{MIN} in the structure **220** relates to the phenomena of resonance and total internal reflection of the radiation within the structure.

[0078] To measure the width of the illuminated structures (e.g., structures **220**) of the patterned mask **210**, the sequence **400** uses the in-situ measuring tool that is adjusted to perform a spectroscopic measuring technique (i.e., measurements of intensity of the radiation versus a wavelength). In one specific embodiment, during the trimming process, the in-situ measuring tool defines a spectral location λ_{MIN} of a minimum in the spectrum of the radiation reflected from the substrate **200** with respect to a pre-selected reference wavelength.

[0079] As a result of selective trapping of a portion (ray R**7**) of the incident radiation, the radiation reflected from the region occupied by the structures **220** (rays R**3**, R**4**, and R**9**) has a low spectral intensity (i.e., a minimum in the spectrum of such reflected radiation) at the wavelength λ_{MIN}. As the trimming process progresses and the width D of the structure **220** decreases, ever shorter wavelengths are trapped in and absorbed by the structure **220**. As such, during the trimming process, the spectral position (i.e., wavelength λ_{MIN}) of the minimum in the spectrum of the reflected radiation changes in a direction of the shorter wavelengths.

[0080] In one embodiment, during the trimming process, the in-situ measuring tool performs real time measurements of the spectral position of the minimum λ_{MIN} in the spectrum of the reflected radiation, as well as of the intermediate width **207** of the structures **220**. The trimming process and in-situ measurements continue until the intermediate width **207** becomes equal to or smaller than the pre-determined (target) width **216**. To increase accuracy of measuring the width **207**, these measurements may be repeated using several test substrates **200** and then statistically processed (e.g., averaged).

[0081] At step **404**, a correlation between the spectral position of the minimum λ_{MIN} in the spectrum of reflected radiation and the intermediate width **207** of the structure **220** is defined using the results of measurements performed during step **402**. Such a correlation allows calculating in real time the starting width **206**, as well as detecting the target width **216** of the structure **220** using the results of the in-situ measurements of

[0082] the spectral position of the minimum λ_{MIN}, that are performed during the trimming process.

[0083] At step **406**, the patterned mask **210** of the product substrate of a batch of such substrates is trimmed using the etch rector comprising the in-situ measuring tool adapted to measure in real time the spectral position of the minimum λ_{MIN} in the spectrum of reflected radiation. In one exemplary embodiment, step **406** uses the DPS II module comprising the in-situ measuring tool described above in reference to step **402**. The in-situ measuring tool is adjusted to illuminate on the product substrate the region occupied be the structures **220** of the patterned mask **210** (e.g., photoresist mask) being trimmed. During the trimming process, the in-situ measuring tool measures in real time the spectral position of the minimum λ_{MIN} and communicates the results of these measurements to a processor (or controller) of the etch reactor.

[0084] At step **408**, the sequence **400** queries if the width (i.e., intermediate width **207**) of the structures **220** has been trimmed to the target width **216** calculated at step **404** above. If the query of step **408** is negatively answered, the sequence **400** proceeds to step **406** to continue the trimming process and real time in-situ measurements of the intermediate width **207** of the structures **220** being trimmed. If the query of step **408** is affirmatively answered, the sequence **400** proceeds to an optional step **118**.

[0085] At step **118**, the layer **202** may be in-situ etched using the trimmed patterned mask **210** as an etch mask. At step **120**, the sequence **400** queries if all product substrates from the batch of such substrates have been processed. If the query of step **120** is negatively answered, the sequence **400** proceeds to step **406**. If the query of step **120** is affirmatively answered, the sequence **400** proceeds to step **122**. At step **122**, the sequence **400** ends.

[0086] FIGS. **6**A-**6**B depict a series of graphs illustrating an example of changes in spectral intensity of radiation reflected from the substrate **200** during the trimming process. A first graph **510** depicts intensity (y-axis **502**) of the incident radiation versus a wavelength (x-axis **504**). A second graph **520** depicts changes, during the trimming process, in intensity (y-axis **522**) of radiation reflected from the region on the substrate **200** occupied by the structures **220** versus a wavelength (x-axis **514**). Referring to FIG. **6**B, at moment T**1**,

prior to the beginning of the trimming process, the spectral intensity of the reflected radiation comprises a minimum **518** having a spectral position (i.e., wavelength λ_{MIN}) **511** that corresponds to the starting width **206** of the structure **220**. As the trimming process continues (illustrated using broken lines), at moment T**2**, the width of the structures **220** decreases to the intermediate width **207** and the spectral position of the minimum **518** changes to the wavelength **513** that is shorter than the wavelength **51**. The spectral position of the minimum **518** decreases to the wavelength **515** when, at moment T**3**, the structure **220** is trimmed to the target width **516**.

[0087] FIG. **7** depicts a graph **600** illustrating exemplary results of the measurements performed on the test substrate **200** during step **402**. More specifically, the graph **600** depicts a width (y-axis **602**) of a structure of the patterned mask **210** versus the spectral position (i.e., wavelength λ_{MIN}) of the minimum in the spectrum of radiation reflected from the region on the substrate **200** occupied by such structures (x-axis **604**). In the graph **600**, the measurements **608** and **606** relate to the wavelength **511** and the starting width **206** of the structure **220**, and the measurements **612** and **610** correspond to the wavelength **515** and the target width **216** of the structure **220**, respectively (wavelengths **511** and **515** are discussed in reference to FIG. **5**B above). Using the graph **600** (shown for simplicity as a linear graph), at step **408**, the target width **216** may be calculated as illustrated using arrow **616**.

[0088] FIGS. **8**A-**8**B depict a flow diagram of one exemplary etch process for monitoring a feature being etched in a material layer as a sequence **650**. The sequence **650** includes a series of processing steps, which may be performed on test and product substrates.

[0089] FIGS. **9**A-**9**B depict schematic, cross-sectional views of a substrate having a feature being etched in a material layer using the inventive method. The images in FIGS. **9**A-**9**B are not depicted to scale and are simplified for illustrative purposes. To best understand the invention, the reader should simultaneously refer to FIGS. **8**A-**8**B and FIGS. **9**A-**9**B.

[0090] The sequence **650** starts at step **651** and proceeds to step **652**. At step **652**, a layer **202** and a patterned mask **210** are illustratively formed on a substrate **200** (e.g., silicon wafer) (FIG. **9**A). For convenience, herein the same schematic, cross-sectional

[0091] views and respective reference numerals may relate to either a test or product substrate **200**.

[0092] The layer **202** may comprise a single material film (e.g., dielectric film, metal film, or any other film used in integrated circuits) or a multi-layered film stack, either unpatterned (as shown) or, alternatively, patterned. During a subsequent etch process, the layer **202** may be etched using the patterned mask **210** as an etch mask. The layer **202** can be formed using any conventional thin film deposition technique, for example, atomic layer deposition (ALD), physical vapor deposition (PVD), chemical vapor deposition (CVD), plasma enhanced CVD (PECVD), and the like that is performed using, e.g., respective processing reactors of CENTURA®, ENDURA®, or other processing systems available from Applied Materials, Inc. of Santa Clara, Calif.

[0093] The patterned mask **210** may generally be in a form of a photoresist mask, an α-carbon (i.e., amorphous carbon) mask, a hard mask, an Advanced Patterning Film™ (APF) available from Applied Materials of Santa Clara, Calif., and the like. In one exemplary embodiment, the patterned mask **210** is a photoresist mask. Illustratively, referring to FIG. **9**A, the patterned mask **210** has openings defining a structure **250** of a width **206** defined therein.

[0094] The photoresist mask **210** may be fabricated using a lithographic process in which a pattern of features of the device to be formed is optically transferred into a layer of photoresist. The photoresist is then developed, unexposed portions of the photoresist are removed, and the remaining photoresist forms the patterned mask **210**. When the patterned mask **210** is a photoresist mask, the layer **202** may further comprise an optional anti-reflective coating (ARC). As sizes of structures of the patterned mask are reduced, inaccuracies in a pattern transfer process may arise from optical limitations inherent to the lithographic process, such as light reflection. The ARC enhances the resolution of the lithographic process by controlling reflection of the light used to expose the photoresist. In one exemplary embodiment, the lithographic process forms the structures **220** having smallest widths **206** of about 80 nm to about 120 nm. Processes of forming the patterned mask **210** are described, for example, in commonly assigned U.S. patent application Ser. No. 10/218,244, filed Aug. 12, 2002, which is incorporated herein by reference.

[0095] At step **654**, the substrate(s) **200** are inspected and topographic dimensions for structures of the patterned mask **210** are measured. In one embodiment, the measured dimensions comprise critical dimensions, i.e., the width **206** of the structures **250** of the patterned mask **210** as well as a thickness for the layer **202** being etched. The width **206** is generally measured on each test substrate **200** of a batch of the test substrates. Such measurements may be performed using a metrology tool that is ex-situ with respect to the etch process. In one exemplary embodiment, such optical measuring tool is the TRANSFORMA™ metrology module of the CENTURA® processing system available from Applied Materials of Santa Clara, Calif. The TRANSFORMA™ metrology module may use one or more non-destructive optical measuring techniques, such as spectroscopy, interferometry, scatterometry, reflectometry, ellipsometry, and the like. The measured parameters include topographic dimensions and profiles of the structures fabricated on substrates, as well as a thickness of either patterned or blanket dielectric and conductive films. Measurements of critical dimensions for the structures **250** are typically performed in a plurality of regions of the substrate **200**, such as a statistically significant number of the regions (e.g., 5 to 9 or more regions), and then averaged for such a substrate.

[0096] At step **656**, the material layer is etched to a predetermined depth. As illustratively shown in FIG. **9**B, step **656** etches the material layer **202** to a pre-determined depth **275**. The etching process is generally an anisotropic etch process (e.g., anisotropic plasma etch process) having a high vertical etch rate and high selectivity for the material of the material layer **202** (e.g., silicon oxide) over the material of the mask **210**.

[0097] Step **656** may be performed using an etch reactor, e.g., the Decoupled Plasma Source (DPS II) module of the CENTURA® system. The DPS II module (discussed below in reference to FIG. **10**) uses an inductive source (i.e., antenna) to produce a high-density plasma.

[0098] In one exemplary embodiment, the material layer **202** comprising silicon dioxide is etched using the DPS II module by providing carbon tetrafluoride (CF_4) at a flow rate of 2 to 200 sccm, argon (Ar) at a flow rate of 10 to 200 sccm, applying power to an inductively coupled antenna between about 200 to 1000 W, applying a cathode bias power between 0 and 300 W, and maintaining a wafer pedestal temperature between 0 and 80 degrees Celsius at a pressure in the process chamber between 2 and 30 mTorr. One illustrative process provides carbon tetrafluoride (CF_4) at a flow rate of 60 sccm,

argon (Ar) at a flow rate of 60 sccm, applies 600 W of power to the inductively coupled antenna, 100 W of cathode bias power and maintains a wafer pedestal temperature of 50 degrees Celsius at a pressure of 4 mTorr.

[0099] In one embodiment, the etch reactor further comprises an in-situ metrology tool configured to measure in real time a metric that corresponds to an etch depth for the material layer being etched (e.g., etch depth **275**). During the etch process, the in-situ metrology tool can illuminate the substrate **200** using a broadband radiation source producing the radiation (i.e., incident radiation) having wavelengths in ultra-violet and deep ultra-violet ranges, e.g., from about 200 to 800 nm. Generally, such a radiation is directed substantially perpendicular to the substrate **200** and illuminates a region having topographic dimensions of less than about 1 mm. More specifically, the in-situ measuring tool illuminates a region of the substrate **200** that is occupied by the structures (i.e., structures **250**) having critical dimensions, such as the width **206**. Details of film thickness measurement and control (or endpoint) by EyeD™ have been disclosed in commonly assigned U.S. Pat. No. 6,413,867, entitled "Film thickness Control Using Spectral Interferometry", issued on Jul. 2, 2002, and U.S. application Ser. No. 10/286,402 entitled "Interferometric Endpoint Determination In A Substrate Etching Process", filed Nov. 1, 2002.

[0100] As described in the references mentioned above, etch depth and etching process endpoint can be determined by counting the constructive or destructive interference fringes (intensity maximum or minimum) of reflected light beams from the wafer (or substrate) surface. An example interference fringe trend signal graph is shown in FIG. **9**C. The period t_1 between peak **301** to peak **302** (or bottom to bottom) equals the period t_2 between peak **302** to peak **303**. The thickness of material etched during t_1 (or t_2) equals $\lambda/2$ (λ is the wavelength being monitored). The equal periods indicate a steady etch rate and constant peak intensity I_1 of peaks **301**, **302** and **303** indicates constant signal intensity. The signal between times T_3 to T_4 shown in FIG. **9**C is then processed using a Discrete Fourier Transform (DFT) to convert the intensity versus time graph to a frequency versus time graph. If the intensity versus time graph is sinusoidal, the transformed intensity versus frequency graph will be a vertical line C**1** at f**1**, as shown in FIG. **9**D. If the intensity graph of FIG. **9**C is not sinusoidal, the transformed graph will be like curve C**2** in FIG. **9**D with peak of the curve at f**1**. f**1** is the inverse of t**1** (1/t**1**), which is the etch time of half of the monitored wavelength ($\lambda/2$). Since the intensity versus time curve is broad versus time, it's not easy to accurately determine the location of peaks **301** and **302** to determine T**3** and T**4**. Without accurate determination of T**3** and T**4**, t**1** (etch time) value cannot be accurately calculated. In contrast, the Discrete Fourier Transformed intensity versus time curve is narrower and can produce much more accurate peak **308** of the graph to accurately determine f**1**, which is the inverse of t**1** (1/t**1**). Since period t_1 equals period t_2, a time duration selected from time T_3 to time T_5 (beyond T_4) would still yield only one peak frequency

[0101] However, in many cases, the interference trend signal graph is not as ideal as that shown in FIG. **9**C. An example of a non-ideal graph of interference fringe intensity versus time is shown as FIG. **9**E. The period t_7 between peak **304** to peak **305** is greater than the period t_8 between peaks **305** and **306**. The decreasing periods indicate an increase in etch rate, possibly due to etch loading effect. The peak intensities I_3, I_4, I_5 and I_6 of peaks **304**, **305**, **306** and **307** also decrease with etch time, which indicates decreasing reflected signals with time. The increasing etch rate with time, in accompanying decreasing signals, could be observed during contact, via and trench etch. FIG. **9**F shows a DFT processed portion of the graph of FIG. **9**E between times T_{10} and T_{11}. Since the period t_6 between T_{10} and T_{11} is shorter than the full intensity cycle (peak to peak), the DFT did not yield a frequency maximum, as seen in FIG. **9**D. If the DFT is performed on the signal between times T_{10} and T_{12}, the resulting intensity versus frequency graph yields a maximum f_2 (1/t**7**) that provides an accurate measure of period t_7. However, if a DFT is performed on the signal between times T_{10} and T_{13}, the resulting intensity versus frequency graph does not yield a singular maximum, but a combined result of dual curves with dual peaks as shown in FIG. **9**H. Thus, it's important to select the appropriate time window over which to perform the DFT. For the intensity curves shown in FIG. **9**E, it becomes important to use an adaptive time window size within which to perform the DFT to accurately determine etch time. For processes with increasing etch rate, the time window for the DFT needs to decrease with time. Similarly, for processes with decreasing etch rate, the time window for the DFT needs to increase with time.

[0102] In one exemplary embodiment, the in-situ measuring tool periodically measures in real time an intermediate etch depth (i.e., etch depth **265**) of the structures **250** being etched in material layer **202** during the etch process (for example, measurements every 100 milliseconds). The etch process and measurements continue until the intermediate depth equals the pre-determined depth **275**.

[0103] At step **658**, a vertical etch rate for the etch process is defined. Such an etch rate is defined using the results of measurements performed during step **656**. Etch depth and etch rate may be measured by tracking reflectance fringes of a particular wavelength (λ) in a time series. For example, the etch depth equals half of the wavelength ($\lambda/2$) when the reflectance pattern reaches a wave cycle. The etch rate can be calculated by dividing the etch depth by the duration.

[0104] At step **660**, a batch of product substrates each having the patterned mask **210** (e.g., photoresist mask) is provided. Prior to the etch process, the width **206** and layer **202** thickness are measured on each product substrate. In one exemplary embodiment, these measurements are performed using the same measuring tool (e.g., TRANSFORMA™ metrology module) and same methodology as described above in step **654** with reference to the test substrates.

[0105] At step **662**, the target etch rate of the structures **250** is calculated for each product substrate using the defined correlation (step **108**) between the starting width **206** (measured at step **660**) of the structure to be etched, vertical etch rate of the etching process, and the pre-determined (target) etch depth **275** of the etched structure.

[0106] At step **664**, the structures **250** are formed in the material layer **202** of the product substrate using an etch rector comprising the in-situ measuring tool adapted to measure in real time the etch depth profile of the structures **250**. During the etch process, the in-situ measuring tool in real time measures the intermediate depth (i.e., height **275**) of the structures **250** being etched and communicates the results of these measurements to a processor (or controller) of the etch reactor. In one exemplary embodiment, the etch process is performed using the DPS II module comprising the in-situ measuring tool described above in reference to step **656**.

[0107] At step **666**, the sequence **650** queries if the etch depth (i.e., intermediate depth **265**) of the structures **250** has been etched to the target depth **275** calculated at step **662** above. If the query of step **666** is negatively answered, the sequence **650** proceeds to step **664** to continue the etching process and real time in-situ measurements of the intermedi-

ate height **275** of the structures **250**. If the query of step **666** is affirmatively answered, the sequence **650** proceeds to step **668**.

[0108] At step **668**, the sequence **650** queries if all product substrates from the batch of such substrates have been processed. If the query of step **668** is negatively answered, the sequence **650** proceeds to step **660**. If the query of step **668** is affirmatively answered, the sequence **650** proceeds to step **670**. At step **670**, the sequence **650** ends.

[0109] FIG. **10** depicts a schematic diagram of an exemplary Decoupled Plasma Source (DPS) II etch reactor **1000** that may illustratively be used to practice the invention. The DPS II reactor **1000** is a processing module of a CENTURA® integrated semiconductor wafer processing system available from Applied Materials, Inc. of Santa Clara, Calif. The particular embodiment of the reactor **1000** shown herein is provided for illustrative purposes and should not be used to limit the scope of the invention.

[0110] The reactor **1000** generally comprises a process chamber **1010** having a substrate pedestal **1016** within a conductive body (wall) **1030**, and a controller **1040**.

[0111] The chamber **1010** is supplied with a substantially flat dielectric ceiling **1020**. Other modifications of the chamber **1010** may have other types of ceilings, e.g., a dome-shaped ceiling. Above the ceiling **1020** is disposed an antenna **1012** comprising one ore more inductive coil elements (two co-axial elements **1012***a* and **1012***b* are shown) that may be selectively controlled. The antenna **1012** is coupled, through a first matching network **1019**, to a plasma power source **1018**. The plasma power source **1018** typically is capable of producing up to 3000 W at a tunable frequency in a range from 50 kHz to 13.56 MHz.

[0112] The substrate pedestal (cathode) **1016** is coupled, through a second matching network **1024**, to a biasing power source **1022**. The biasing source **1022** generally is a source of up to 500 W at a frequency of approximately 13.56 MHz that is capable of producing either continuous or pulsed power. In other embodiments, the source **1022** may be a DC or pulsed DC source.

[0113] A controller **1040** comprises a central processing unit (CPU) **1044**, a memory **1042**, and support circuits **1046** for the CPU **1044** and facilitates control of the components of the process chamber **1010** and, as such, of the etch process, as discussed below in further detail.

[0114] An etchant gas and a passivation gas are provided to the process chamber **1010** from a gas panel **1038**. The etchant gas is typically supplied through one ore more inlets **1026** (two inlets are shown) located above the substrate pedestal **1016**. The passivation gas is supplied from the gas panel **1038** through a plurality of inlets **1028** (e.g., openings, injectors, and the like). The inlets **1028** (two inlets are shown) are generally located substantially equidistantly around the substrate pedestal **1016** approximately coplanar with a semiconductor wafer **1014** being etched. Embodiment and location of the inlets **1028** are selected to provide high controlled concentration of the passivation gas in a peripheral region (i.e., annular region near the edge) of the wafer **1014**.

[0115] The etchant gas and the passivation gas are delivered to the process chamber **1010** using separate gas conduits (conduits **1037** and **1039**, respectively) and do not mix until they are dispersed into a reaction volume **1053** of the chamber. In the depicted embodiment, the etchant gas is provided to the inlets **1026** using an annular gas channel **1027** and, similarly, the passivation gas is provided to the inlets **1028** using an annular gas channel **1029**. The gas channels **1027** and **1029** may be formed in the wall **1030** or in gas rings (as shown) that are coupled to the wall **1030**. In the process chamber **1010**, the etchant and passivation gases form a gaseous mixture **1050**. During an etch process, the gaseous mixture **1050** is ignited into a plasma **1055** by applying power from the plasma source **1018** to the antenna **1012**.

[0116] The gas pressure in the chamber **1010** is controlled using a throttle valve **1063** and a vacuum pump **1036**. The temperature of the wall **1030** may be controlled using liquid-containing conduits (not shown) that run through the wall **1030**. Typically, the chamber wall **1030** is formed from a metal (e.g., aluminum (Al), stainless steel, and the like) and coupled to an electrical ground **1034**.

[0117] In operation, the temperature of the wafer **1014** is controlled by stabilizing a temperature of the substrate pedestal **1016**. In one embodiment, a backside gas (e.g., helium (He)) from a gas source **1048** is provided via a gas conduit **1049** to channels that are formed in the pedestal surface under the wafer **1014**. The backside gas is used to facilitate heat transfer between the pedestal **1016** and the wafer **1014**. During the processing, the pedestal **1016** may be heated by an embedded resistive heater **1032** to a steady-state temperature and then the helium gas facilitates uniform heating of the wafer **1014**. Using such thermal control, the wafer **1014** may be maintained at a temperature between about 0 and 350 degrees Celsius.

[0118] In one embodiment, the substrate pedestal **1016** comprises an electrostatic chuck **1060**, an edge ring **1015**, the resistive heater **1032**, a heat sink **1066**, and a mounting assembly **1006**. The electrostatic chuck **1060** comprises at least one clamping electrode **1080** and is controlled by a chuck power supply **1076**. The resistive heater **1032** generally comprises at least one heating element **1082** and is regulated by a heater power supply **1078**. In alternative embodiments, the substrate pedestal **1016** may comprise a susceptor clamp ring, a mechanical chuck, and the like substrate retention mechanism.

[0119] In operation, the lift mechanism **1062** is used to raise the wafer **1014** off the substrate support **1016** or to lower the substrate onto the substrate support. Generally, the lift mechanism **1062** comprises a plurality of lift pins **1072** (one lift pin is shown) that travel through respective guide holes **1088**. The process chamber **1010** also comprises conventional systems for process control, internal diagnostic, end point detection, and the like. Such systems are collectively shown as support systems **1007**.

[0120] Those skilled in the art will understand that other forms of etch chambers may be used to practice the invention, including chambers with remote plasma sources, electron cyclotron resonance (ECR) plasma chambers, and the like.

[0121] To facilitate control of the process chamber **1010**, the controller **1040** may be one of any form of general-purpose computer processor that can be used in an industrial setting for controlling various chambers and sub-processors. The memory, or computer-readable medium, **1042** of the CPU **1044** may be one or more of readily available memory such as random access memory (RAM), read only memory (ROM), floppy disk, hard disk, or any other form of digital storage, local or remote. The support circuits **1046** are coupled to the CPU **1044** for supporting the processor in a conventional manner. These circuits include cache, power supplies, clock circuits, input/output circuitry and subsystems, and the like. The inventive method is generally stored in the memory **1042** as a software routine. Alternatively, such software routine may also be stored and/or executed by a second CPU (not shown) that is remotely located from the hardware being controlled by the CPU **1044**.

[0122] An example of an etch system that is integrated with an ex-situ metrology tool with the capability of measuring CDs and film thickness is Applied Materials' Transforma system **800** (FIG. **11**). Detailed information describing Applied Materials' Transforma system has been disclosed in a commonly assigned U.S. patent application Ser. No. 10/428,145, titled "Method and Apparatus for Controlling Etch Processes During Fabrication of Semiconductor Devices", filed on May 1, 2003. The system comprises a chamber or "mainframe" **801**, such as the Centura™ processing system for mounting a plurality of processing chambers **802**, e.g., conventional etch reactors, such as DPSII™ silicon etch chambers and one or more transfer chambers **803**, also called "load locks". In one embodiment of the present invention, four etch processing chambers **802** are mounted to the mainframe **801**. In one exemplary embodiment, three etch processing chambers **802** are used for etching and one is optionally used for post-etch cleaning (i.e. removing photoresist polymers and other residue from wafers after etching). A robot **804** is provided within the mainframe **801** for transferring wafers between the processing chambers **802** and the transfer chambers **803**. The transfer chambers **803** are connected to a factory interface **805**, also known as a "mini environment", which maintains a controlled environment. A metrology (or measurement) tool **806** could be integrated in the load lock area **805** and with high-speed data collection and analysis capabilities, every wafer that enters the system **800** can be measured for thickness before and after etch processing. The metrology tool **806** could also be placed at different location within the process system **800**. One or more of the process chambers **802** could also be deposition chambers, since the concept of the invention also applies to deposition process.

[0123] The invention may be practiced using other etch processes wherein parameters may be adjusted to achieve acceptable characteristics by those skilled in the arts by utilizing the teachings disclosed herein without departing from the spirit of the invention.

[0124] The invention may be practiced using other semiconductor wafer processing systems wherein the processing parameters may be adjusted to achieve acceptable characteristics by those skilled in the arts by utilizing the teachings disclosed herein without departing from the spirit of the invention.

[0125] Although the forgoing discussion referred to endpoint detection during trimming patterned masks, fabrication of the other devices and structures used in the integrated circuits can benefit from the invention.

[0126] While the foregoing is directed to the illustrative embodiment of the present invention, other and further embodiments of the invention may be devised without departing from the basic scope thereof, and the scope thereof is determined by the claims that follow.

What is claimed is:

1. A system for monitoring an etch process, comprising:
at least one reactor to perform an etch process;
at least one metrology module to provide pre-etch measurement information to the at least one etch reactor; and
at least one substrate robot, wherein the at least one reactor comprises an etch process measuring module for monitoring an etch process endpoint in the etch reactor.

2. The system of claim **1** wherein the at least one etch reactor is a plasma reactor.

3. The system of claim **1** wherein the at least one metrology module uses a non-destructive optical measuring technique.

4. The system of claim **1** wherein the etch process measuring tool uses an interferometric measuring technique.

5. The system of claim **1** wherein the etch process measuring tool further comprises:
a source of a radiation to illuminate a region on the substrate; and
an interferometer.

6. The system of claim **1** wherein the source of radiation provides radiation substantially perpendicular to the substrate.

7. The system of claim **1** wherein the source of radiation provides radiation at wavelengths in a range from about 200 to 800 nm.

8. The system of claim **5** wherein the source of radiation modulates an intensity of the radiation at a frequency of about 10 Hz.

9. An in-situ metrology tool, comprising:
at least one plasma reactor to perform wafer processing;
at least one measurement module, coupled to the at least plasma reactor, for measuring at least one of a thickness of a layer on a substrate and a critical dimension; and
at least one plasma state monitoring module, coupled to the at least one plasma reactor, for monitoring a plasma state within the at least one plasma reactor.

10. The tool of claim **9** wherein the thickness measurement module uses an interferometric measuring technique.

11. The tool of claim **9** wherein the critical dimension measurement module uses a non-destructive optical measuring technique.

12. The tool of claim **9** wherein the plasma state monitoring module usages an optical electromagnetic emission measuring technique.

13. The tool of claim **9** wherein the plasma reactor is a plasma etch reactor.

14. A method of processing data collected by an in-situ metrology tool of a semiconductor wafer processing system, comprising:
examining data representing signal intensity versus time as collected by the in-situ metrology tool; and
selecting, based on the data, a time window for performing a Discrete Fourier Transformation upon at least one portion of the data.

15. The method of claim **14**, further comprising:
if the data representing signal intensity versus time indicate decreasing peak to peak periods, reduce the time window; and
if the data representing signal intensity versus time data indicate increasing peak to peak periods, increase the time window.

* * * * *