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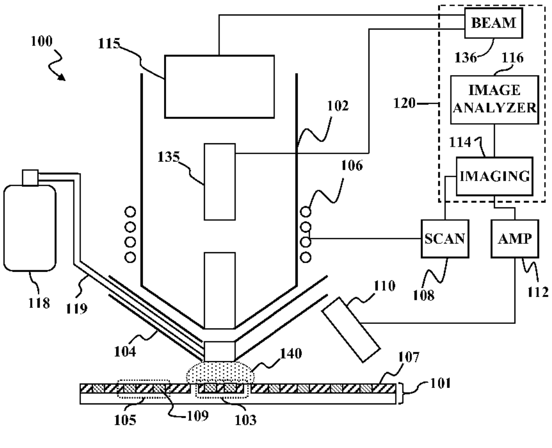
(54) Title: ETCH SELECTIVITY ENHANCEMENT, DEPOSITION QUALITY EVALUATION, STRUCTURAL MODIFICATION AND THREE-DIMENSIONAL IMAGING USING ELECTRON BEAM ACTIVATED CHEMICAL ETCH



(57) Abstract: Etch selectivity enhancement during electron beam activated chemical etch (EBACE), methods and apparatus for evaluating the quality of structures on an integrated circuit wafer using EBACE, a method for modifying a surface of a substrate (or a portion there of), methods and apparatus for imaging a structure and an associated processor-readable medium are disclosed. A target or portion thereof may be exposed to a gas composition of a type that etches the target when the gas composition and/or target are exposed to an electron beam. By directing an electron beam toward the target in the vicinity of the gas composition, an interaction between the electron beam and the gas composition etches a portion of the target exposed to both the gas composition and the electron beam.

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ETCH SELECTIVITY ENHANCEMENT, DEPOSITION QUALITY EVALUATION, STRUCTURAL MODIFICATION AND THREE-DIMENSIONAL IMAGING USING ELECTRON BEAM ACTIVATED CHEMICAL ETCH

FIELD OF THE INVENTION

This invention generally relates to semiconductor fabrication and more particularly to electron beam activated chemical etching (EBACE).

BACKGROUND OF THE INVENTION

A technique known as electron beam activated chemical etch (EBACE) has been developed as an analytical tool in semiconductor fabrication. In this technique an etchant, typically in the form of a gas or vapor, is introduced into the field of view of a scanning electron microscope proximate the surface of a target, such as an integrated circuit device. The etchant is usually one that is known to etch the target material upon electron-beam induced activation. The electron beam from the electron microscope activates the etchant resulting in etching of the target surface in locations exposed to both the etchant and the electron beam. The resulting localized etching of the target surface can be combined with real time imaging of the surface as it is etched.

It is within this context that embodiments of the present invention arise.

Tungsten plugs transfer current between upper and lower interconnect levels in a semiconductor integrated circuit. Holes are formed in an insulating layer by dry etching. The tungsten is deposited in the holes by a chemical vapor deposition (CVD) process. Being formed via a surface driven chemical process, the tungsten grows from the bottom and walls of the holes. Growth of the tungsten stops when the holes are closed. The holes usually do not close perfectly because of growing layer surface roughness. Because the holes are not perfectly filled, there is usually a seam in the center of the tungsten plug. After tungsten deposition, an etch or chemical mechanical polishing (CMP) step removes the overburden. Both dry etch and CMP involve significant degree of chemical reaction with the tungsten overburden. This reaction is active on all kinds of interfaces. Usually the seam becomes the most chemically vulnerable plug location, which is etched out during CMP or dry etch. Often one finds a keyhole in the center of the plug as a result of the chemical etching. The holes affect the plug electrical properties and electromigration performance and also trap chemicals inducing corrosion effects. Therefore it is important to evaluate the deposition quality of the tungsten plugs.

The deposition processes parameters may be adjusted to optimize the quality of the plugs. However, to do so it is necessary to determine how many plugs have unacceptably large voids. This typically requires etching away the tungsten until the voids in the plugs become visible. Although such etching may be done by EBACE, this technique typically involves sacrificing some of the devices on a particular wafer, which reduces yield and increases costs.

Thus, there is a need in the art for a method of determining the quality of tungsten deposition that overcomes the above disadvantages.

BRIEF DESCRIPTION OF THE DRAWINGS

Other objects and advantages of the invention will become apparent upon reading the following detailed description and upon reference to the accompanying drawings in which:

FIG. 1A is a schematic diagram of an electron beam activated chemical etch (EBACE) system adapted for etch selectivity enhancement according to an embodiment of the present invention.

FIG. 1B is a block diagram of the system of FIG. 1A.

FIG. 2 is a flow diagram illustrating an example of a method for etch selectivity enhancement during EBACE according to an embodiment of the present invention.

FIGs. 3A-3C are cross-sectional schematic diagrams illustrating etch selectivity enhancement during EBACE according to an embodiment of the present invention.

FIGs. 4A-4C are cross-sectional schematic diagrams illustrating etch selectivity enhancement during EBACE according to an alternative embodiment of the present invention.

FIGs. 5A-5D are cross-sectional schematic diagrams illustrating etch selectivity enhancement by variation of an electron beam scanning pattern during EBACE according to another alternative embodiment of the present invention.

FIGs. 6A-6D are cross-sectional schematic diagrams illustrating etch selectivity enhancement through the use of a passivating material during EBACE according to another alternative embodiment of the present invention.

FIGs. 7A-7D are three-dimensional schematic diagrams illustrating etch selectivity enhancement during EBACE through embedding of structures in a target.

FIG. 8A is a schematic diagram of an electron beam activated chemical etch (EBACE) apparatus adapted for etch selectivity enhancement through use of a focused ion beam according to an embodiment of the present invention.

FIG. 8B is a block diagram of the apparatus of FIG. 8A

FIG. 9A is a schematic diagram of an electron beam activated chemical etch (EBACE) apparatus adapted for etch selectivity enhancement through use of a decontaminating gas.

FIG. 9B is a top view schematic diagram of a gas injection manifold that may be used with the apparatus of FIG. 9A.

FIG. 10 is a flow diagram illustrating an example of a method for evaluating integrated circuit structures according to an embodiment of the invention.

FIG. 11A is a plan view schematic diagram illustrating a portion of an integrated circuit wafer including an apparatus for evaluating integrated circuit structures.

FIG. 11B is a plan view schematic diagram of a test wafer illustrating evaluation of integrated circuit structures according to an embodiment of the invention.

FIG. 12 is a flow diagram illustrating an example of a method for structural modification using EBACE according to an embodiment of the present invention.

FIGs. 13A-13C are cross-sectional schematic diagrams illustrating structural modification using EBACE according to an embodiment of the present invention.

FIGs. 14A-14D are cross-sectional schematic diagrams illustrating optical component formation by means of variation of an electron beam scanning pattern during EBACE according to another alternative embodiment of the present invention.

FIGs. 15A-15D are schematic cross-sectional side views illustrating diffractive optical components formation by means of variation of an electron beam scanning pattern during EBACE according to another alternative embodiment of the present invention.

FIGs. 16A-16D are top views of diffractive optical components shown on FIGs.5A-5D respectively.

FIGs. 17A-17D are schematic cross-sectional side views illustrating fin FET device formation by means of selective etching/deposition using EBACE method according to another alternative embodiment of the present invention.

FIG. 18A-18B are schematic cross sectional and pattern top views of Alternating Phase-Shift Mask formation using EBACE method.

FIG. 19A-19D are schematic cross sectional views illustrating method for etching copper patterns using EBACE method combined with oxygen ion beams according to another alternative embodiment of the present invention.

FIG. 20 is a schematic diagram of an electron beam activated chemical etch (EBACE) system adapted for structures de-layering according to an embodiment of the present invention.

FIG. 21 is a flow diagram illustrating an example of a method for 3-D image reconstruction using EBACE according to an embodiment of the present invention.

FIGs. 22A-22B illustrate a process of schematic 3-D structure reconstruction from a number of image frames obtained using EBACE according to an embodiment of the present invention.

DESCRIPTION OF THE SPECIFIC EMBODIMENTS

Although the following detailed description contains many specific details for the purposes of illustration, anyone of ordinary skill in the art will appreciate that many variations and alterations to the following details are within the scope of the invention. Accordingly, the exemplary embodiments of the invention described below are set forth without any loss of generality to, and without imposing limitations upon, the claimed invention.

FIGs. 1A-1B illustrate an example of an electron beam activated chemical etch (EBACE) system **100** adapted for use with embodiments of the present invention. As shown in FIG. 1A, the system **100** generally includes a scanning electron microscope having an electron beam column **102** with an electron source **115**, beam optics **135** an immersion lens **104**. The electron beam column **102** may be controlled by electronics **136**, referred to herein as an e-beam driver. The e-beam driver **136** may control the electron source **115**, beam optics **135** and immersion lens **104**.

Electrons from the electron beam column **102** are focused onto a target surface **101**, which may be an integrated circuit wafer or a test wafer. The electrons are scanned across the surface of the target **101** by magnet deflecting fields provided by one or more scanning coils **106**. Current is provided to the coils **106** via a scanner driver **108**. Electrons striking the target **101** are either backscattered or initiate secondary emission. Either way a detector **110** generates a signal proportional to the amount of backscattering or secondary emission. The signal may be amplified by an amplifier **112**. The amplified signal and a signal from the scanner driver **108** are combined by an image generator **114** to produce a high-contrast, magnified image of the surface of the target **101**. The images are analyzed by an image analyzer **116**.

The target **101** may optionally include one or more test structures **103**. The test structures typically correspond in dimensions (e.g., diameter and depth) to one or more integrated circuit structures **105** that may be located on the target **101** or on another wafer. By way of example, and without loss of generality, the integrated circuit structures **105** may be conductive interconnects between adjacent layers of an integrated circuit device. Such interconnects may be formed by etching holes through a layer of insulating material **107** and filling the holes with a conductive or semiconductive material **109**, e.g., tungsten or silicon.

An electron activated etching gas or vapor composition **117** is introduced from one or more remote sources **118** via a conduit **119**. It is desirable to introduce the etching gas or vapor as close as possible to the point on the surface of the target **101** impacted by the electrons from the electron beam column **102**. By way of example, the etching gas or vapor may be introduced between two adjacent electrodes of the immersion lens **104**. The electrons activate localized etching of the target surface **101**. Images of the etched surface generated by the image analyzer may be analyzed by the image analyzer **116**. The image analysis determines a measure of quality of the test structures **103**, e.g., the number and size of voids resulting from the formation of interconnect structures.

As shown in the block diagram of FIG. 1B, the image generator **114** and image analyzer may be part of a controller **120**. The controller **120** may be a self-contained microcontroller. Alternatively, the controller **120** may be a general purpose computer configured to include a central processor unit (CPU) **122**, memory **124** (e.g., RAM, DRAM, ROM, and the like) and well-known support circuits **128** such as power supplies **121**, input/output (I/O) functions **123**, clock **126**, cache **134**, and the like, coupled to a control system bus **130**. The memory **124** may contain instructions that the CPU **122** executes to facilitate the performance of the system **100**. The instructions in the memory **124** may be in the form of the program code **125**. The code **125** may control, e.g., the electron beam voltage and current produced by the source **115**, the focusing of the beam with the beam optics **135** and the immersion lens **104** and the scanning of the electron beam by the coils **106** and the formation of images with the signal from the detector **110** in a conventional fashion. The code **125** may also implement analysis of the images.

The code **125** may conform to any one of a number of different programming languages such as Assembly, C++, JAVA or a number of other languages. The controller **120** may also include an optional mass storage device, **132**, e.g., CD-ROM hard disk and/or removable storage, flash memory, and the like, which may be coupled to the control system bus **130**. The controller **120** may optionally include a user interface **127**, such as a keyboard, mouse, or light pen, coupled to the CPU **122** to provide for the receipt of inputs from an operator (not shown). The controller **120** may also optionally include a display unit **129** to provide information to the operator in the form of graphical displays and/or alphanumeric characters under control of the processor unit **122**. The display unit **129** may be, e.g., a cathode ray tube (CRT) or flat screen monitor.

The controller **120** may exchange signals with the imaging device scanner driver **108**, the e-beam driver **135** and the detector **110** or amplifier **112** through the I/O functions **123** in response to data and program code instructions stored and retrieved by the memory **124**. Depending on the configuration or selection of controller **120** the scanner driver **108** and detector **110** or amplifier **112** may interface with the I/O functions via conditioning circuits. The conditioning circuits may be implemented in hardware or software form, e.g., within code **125**.

FIG. 2 illustrates a method **200** for etch selectivity enhancement during electron beam activated chemical etch (EBACE). At **202** the target **101** or a portion thereof is exposed to the gas composition **117**. The gas composition is of a type that etches nearby portions of the target **101** when the gas composition **117** is exposed to the electron beam. At **204** the electron beam is directed toward the target **101** in the vicinity of the gas composition **117**. An interaction between the electron beam and the gas composition **117** etches a portion of the target **101** exposed to both the gas composition **117** and the electron beam. At **206** a selectivity of etching of the target due to interaction between the electron beam and gas composition **117** is enhanced.

There are a number of different techniques for enhancing etch selectivity according to embodiments of the present invention. For example, as illustrated in FIGs. 3A-3C, a target **300** may include first and second regions **302**, **304** respectively made of first and second different materials that are exposed to an electron beam **301** and gas composition **303**. Etch selectivity may be enhanced if a gas composition **303** is chosen such that the interaction between the electron beam **301** and gas composition **303** converts the first material into the second material as shown in FIG. 3B. As a result of such conversion, the first and second regions **302**, **304** may be etched at substantially the same rate. By way of example, the second material may be an oxide or carbide of the first material. Specifically, the first material may be silicon and the second material may be silicon oxide. The gas composition **303** may include a carbon-containing organic compound, an etchant and oxygen. By way of example, if the first region **302** is made of silicon and the second region **304** is made of silicon oxide the carbon-containing organic compound may be a hydrocarbon, such as methane or ethylene, and the etchant may be xenon di-fluoride (XeF_2).

Depending on the materials of the first and second regions, many other possible combinations of carbon-containing and etchant gases may be used. For example, nitrogen (N_2), hydrogen (H_2) and water vapor (H_2O) may be used as etchants for organic materials. Furthermore, some gases may be used as either an etchant or passivating gas. For example, carbon monoxide gas may be used as an etch gas to form volatile carbonyl compounds, e.g., from tungsten, upon interaction with the electron beam and the material the first or second region. Carbon monoxide may also be used to passivate tungsten and convert it to, e.g., tungsten carbide.

Variations on the technique described above with respect to FIGs. 3A-3C may enhance etch selectivity by facilitating etching of different regions of the target at different rates. For example, as illustrated in FIGS. 4A-4C a target **400** may include a first region **402** containing a first material and a second region **404**. The first and second regions **402**, **404** are exposed to an electron beam **401** and a gas composition **403**. Selectivity of etching of the target may be enhanced if the gas composition is selected such that an interaction between the electron beam and gas composition covering the second material but not the first material with a third material **406** as shown in FIG. 4B. Preferably, the third material **406** is one that reduces a rate of etching of the second material relative to the first material. As a result, the second region **404** is etched at a lower rate than the first region **402**, as shown in FIG. 4C. By way of example the third material **406** may be carbon. To deposit carbon, the gas composition **403** may include a carbon-containing organic compound, an etchant and oxygen. Specifically, the carbon-containing organic compound may be a hydrocarbon, such as methane or ethylene, and the etchant may be xenon di-fluoride (XeF_2). Other carbon containing gases include carbon monoxide, as described above. Alternative etchants include nitrogen, hydrogen and water vapor and carbon monoxide, as described above.

In other embodiments of the invention the selectivity of etching may be enhanced by adjusting an electron beam energy, an electron beam current or a scanning pattern of the electron beam from the electron beam column **102**. For example as shown in FIG. 5A the scanning pattern of the electron beam **501** from a beam column **502** may be adjusted by varying a dwell time or a repetition rate of the electron beam **501** for different regions **A**, **B**, **C** of a target **504**. By way of example, the dwell time may be larger for regions **A** and **C** compared to region **B**. Consequently, interaction between the electron beam an electron-beam activated gas composition **503** and the target **504** results in a greater etching of regions **A** and **C** compared to region **B** as shown in FIG. **5B**. The dwell time and/or repetition rate of the electron beam may be controlled, e.g., through appropriate configuration of the code **125** running on the controller **120**. As shown in FIG. 5C, the scanning pattern may be varied in such a way as to etch two dimensional patterns in regions **A**, **B** and **C** to different depths.

It is noted that if the contribution of the gas composition **503** to etching of the target **504** by the electron beam **501** does not vary significantly, the etching may be very finely controlled through precise control of the electron beam **501**. To keep the contribution of the gas composition **503** to the etching from varying significantly the scanning pattern of the electron beam **501** may be adjusted for different regions of the target **504**, e.g., by varying dwell time and/or repetition rate without varying the gas composition **503**. As used herein varying the gas composition **503** may include, but is not limited to varying stoichiometric ratios and/or flow rates, etc for gases making up the gas composition **503**.

As shown in FIG. 5D, the scanning pattern of the electron beam **501** may vary as a function of depth. For example, etching the target **504** to a sufficient depth may form a feature having one or more sidewalls **506**. If the scanning pattern remains more or less unchanged as a function of depth, the etching of the target **504** tends to attack the sidewall **506** resulting in a slanted sidewall, as indicated by the dotted line. To avoid this effect the scanning pattern of the electron beam **501** may be varied as a function of etch depth **d** to produce a more or less vertical sidewall (i.e., a sidewall that is substantially perpendicular to a plane of the target **504**. By way of example, a width **w** of the scanning pattern may be varied as a function of depth of etching of the target **504**. The scan width **w** may be defined as a range of excursion of the electron beam **501** along a direction parallel to a plane of the target. For example, if the target plane is more or less horizontal, the scan width **w** may be a horizontal range of excursion of the electron beam **501**. The horizontal range of excursion of the electron beam **501** may be adjusted, e.g., through appropriate control of the scanner **106** with the scanner driver **108**. To fabricate the sidewall **506** such that it is substantially vertical, the scanning pattern of the electron beam **501** may be varied as a function of time such that the scan width **w** narrows as a feature is etched more deeply into the target **504**.

In alternative embodiments, the selectivity of etching of a target **602** with an electron beam **601** and gas composition **603** may be enhanced by depositing a passivating material **604** on selected portions of the target **602** as shown in FIGs. 6A-6D. Preferably, the passivating material **604** is one that reduces a rate of etching of the material of the target **602** due to interaction between the electron beam **601** and gas composition **603**. By way of example, the passivating material **604** may be deposited on one or more sidewalls of one or more features formed on the target. For example, as shown in FIG. 6A, the passivating material may be deposited over sidewalls **606** of a negative feature **605** such as a trench or via. Alternatively, as shown in FIG. 6C, the passivating material **604** may be deposited over a positive feature **607**, e.g., a line or mesa.

The passivating material **604** inhibits etching of the sidewalls **606** while allowing etching of nearby portions of the target. As a result, the sidewalls **606** retain their shape and/or orientation as the thickness of the nearby portions is reduced. In the examples shown in FIGs. 6A-6D the target may have portions made of different materials. For example, as shown in FIGs. 6A-6B, the negative feature **605** may be formed in a layer of silicon oxide **608** that overlies a layer of silicon **610**. Alternatively, as shown in FIGs. 6C-6D, the positive feature **607** may be formed from a layer of silicon oxide **608** that overlies a layer of silicon **610**. By appropriate choice of the gas composition **603** and passivating material **604**, the electron beam **601** may etch the silicon oxide **608**, but not the silicon **610** as shown in FIG. 6B and FIG. 6D. For example, the gas composition **603** may include a carbon-containing organic component (e.g., a hydrocarbon such as methane or ethylene) such that carbon is deposited as the passivating material **604**. In such a case, it is desirable that the gas composition **603** include an etchant that, upon activation by the electron beam **601**, preferentially etches portions of the target **602** that are not coated with carbon. An example of such an etchant is xenon di-fluoride (XeF_2). Alternative etchants include nitrogen, hydrogen, water vapor and carbon monoxide, as described above. Other carbon containing gases include carbon monoxide, as described above.

In some embodiments, the gas composition **603** may include an inert gas (e.g., Argon or Nitrogen) to further enhance etch selectivity. The inert gas, or a portion thereof, may be ionized the electron beam **601** thereby producing ions **611**. By applying an appropriate voltage to the target **602** the ions **611** may bombard the target **602**. The ion bombardment may advantageously liberate oxygen from oxygen-containing portions of the target **602**. For example, ion bombardment may release oxygen from the silicon oxide **608** but not the silicon **610**. The oxygen released by the bombardment may remove passivating material **604** (e.g., carbon) from the silicon oxide **608** but not nearby portions of the silicon **610**. As a result, the silicon oxide **608** may be subject to etching by interaction with the electron beam **601** and gas composition **603** but the silicon **610** is not.

In alternative embodiments, the gas composition **603** may include a reactive gas. The reactive gas may react with the passivating material **604** such that the passivating material **604** is removed from the target **602**. For example, the gas composition **603** may include oxygen, which may react with carbon passivating material. In other embodiments, nitrogen (N_2) may be used as the reactive gas, e.g., to form volatile cyanides (CN) from the carbon and facilitate its removal.

In other embodiments, the selectivity of etching of a target may include embedding within the target a structure that reacts differently with the electron beam and gas composition than other nearby portions of the target. For example, as shown in FIG. 7A a target **702** may have embedded within it one or more structures **704A**. The material composition of the structures **704A** is selected such that the interaction between an electron beam **701** and the gas composition **703** etches more the structures **704A** more rapidly than the other nearby portions

706 of the target **702**. Rapid disappearance of the structures **704A** as shown in FIG. 7B may serve as an endpoint indicator for an EBACE etching process.

Alternatively, structures **704B**, sometimes referred to as “floaters” may be embedded in the target **702** as shown in FIG. 7C. The material composition of the “floater” structures **704B** may be selected such that the interaction between the electron beam **701** and the gas composition **703** etches the floater structures **704** more slowly than the other nearby portions **706** of the target **702**. As a result, the appearance of the structures **704** may serves as an endpoint indicator for an EBACE etch process as shown in FIG. 7C. In general, it is desirable that the material of the “floater” structures **704B** is one that does not form volatile byproducts upon an EBACE reaction with the etchant in the gas composition **703**. Examples of suitable materials for such floater structures **704B** include gold and hafnium carbide, which is generally not etchable by EBACE using certain etchants, such as XeF_2 in the gas composition **703**. Other examples include silicon oxide and silicon nitride, which would be etched more slowly by a XeF_2 EBACE reaction than nearby regions of silicon.

In some cases, the target **101** may contain one or more materials that are not removable by etching due to the interaction between the electron beam and gas composition **117**. For example, certain metals, such as Nickel, Cobalt, Gold and Hafnium, typically do not form volatile products when subject to EBACE. Such materials may be present as impurities or may be present as part of a structure that is to be removed. In such situations, selectivity of etching of the target may be enhanced by using a focused ion beam in conjunction with EBACE to remove such materials from the target. FIGs. 8A-8B illustrate an example of an apparatus **800** for implementing such a technique. The apparatus **800** may generally include the electron beam column **102**, with its associated components, e.g., immersion lens **104**, scanner coils **106**, electron source **115**, beam optics **135** e-beam driver **136**, controller **120**, etc. as described above with respect to FIGs. 1A-1B. The apparatus **800** may also include remote gas sources **118** and conduit **119** adapted to introduce the electron activated gas composition **117** to the vicinity of a target **101** as described above.

In addition to the above-described components, the apparatus **800** includes a focused ion beam source **802**. The ion beam source **802** may include an ion source **804** where ions are generated, ion beam optics **806** that extract and/or collimate an ion beam **801** from the source **804** and an immersion lens **808** adapted to focus the ion beam **801** onto the target **101** with sufficient beam energy and beam current to sputter material from the surface of the target.

The ion beam source **802** may also include a beam scanning mechanism, e.g., coils or raster plates to steer the ion beam **801** over the target **101**. The components of the ion source **802** may controlled by electronics **810**, referred to herein as an ion beam driver. The ion beam driver **810** may be coupled to the controller **120**, e.g., via the I/O functions **123**. The program code **125** may include instructions that control sputtering of the selected portions of the target with the ion beam **801**.

In other embodiments of the invention etch selectivity during EBACE may be enhanced by including in the gas composition **117** one or more decontaminating gases that react with the target **101** in such a way as to remove one or more contaminants from the target and/or prevent contamination of the target **101** by the one or more contaminants. By way of example, carbon contamination may be removed and/or prevented in this fashion through the inclusion of oxygen in the gas composition **117** as a decontaminating gas. Alternatively, decontaminating gases may include nitrogen (N_2), argon (Ar), xenon (Xe), or hydrogen (H_2).

FIG. 9 depicts an example of an apparatus **900** that may be used in embodiments of the invention involving the use of decontaminating gases. The apparatus **900** may generally include the electron beam column **102**, with its associated components, e.g., immersion lens **104**, scanner coils **106**, electron source **115**, beam optics **135** e-beam driver **136**, controller **120**, etc. as described above with respect to FIGs. 1A-1B. The apparatus **900** may also include multiple remote gas sources **118A**, **118B** and conduits **119A**, **119B** adapted to introduce the electron activated gas composition **117** to the vicinity of a target **101** as described above. The remote gas source **118A**, **118B** may respectively supply an etchant and a decontaminating gas to the gas composition **117**.

Preferably, the decontaminating gas is delivered in close proximity to the target with a high pressure profile proximate to an intersection between the beam of electrons and the target. Decontaminating gases such as Nitrogen, Argon, Xenon and Hydrogen may be used to generate a localized plasma by pulsing an extraction field applied in the vicinity of the target. A pulsed voltage **V** may optionally be applied between the immersion lens **104** and the target **101** to provide the pulsed extraction field. A source of the voltage **V** may be switched on and off to provide the desired pulsing. Ions from the plasma may bombard the target and sputter react with or otherwise remove contaminants from the target **101**.

In some embodiments, it is desirable to deliver the decontaminating gases using a gas system having separate gas injection pathways for gases that would otherwise react undesirably if mixed in a single feed line. Examples of combinations of gases that may undesirably react in a feed line include corrosives and oxidizers, e.g., chlorine and water vapor. FIG. 9B depicts an example of a gas manifold **910** that may be used in the apparatus **900** to deliver the components of the gas composition **117** (including decontaminating gases) with separate gas feed lines. The manifold **910** may be attached to or incorporated into the immersion lens **104** as shown in FIG. 9A. The manifold **910** includes a ring **912** having passages **914** that can be coupled to separate feed lines, e.g., conduits **119A**, **119B** at an outer edge of the ring **912**. The passages **914** communicate through the ring **912** to an inner edge. Needles **916** coupled to the passages **914** at the inner edge direct gases towards a central region proximate the target. The gas pressure profile of the gas composition **117** (and plasma) may be adjusted by appropriate choice of the number of passages and needles, the inner diameter of the ring **912**, the inner diameters and lengths of the needles **916** and the flow rates of the gases.

Another embodiment of the invention relates to a method for evaluating the quality of structures on an integrated circuit wafer. Test structures formed either on the integrated or on a test wafer are exposed to an electron beam and an electron-beam activated chemical etching gas or vapor. The electron-beam activated etching gas or vapor etches the test structures, which are analyzed after etching to determine a measure of quality of the test structures. The measure of quality may be used in a statistical process control to adjust the parameters used to form device structures on the integrated circuit wafer.

In a particular embodiment of the invention the test structures are formed on an integrated circuit wafer having two or more die. Each die has one or more integrated circuit structures. The test structures are formed on scribe lines between two or more adjacent die. Each test structure may correspond in dimensions and/or composition to one or more of the integrated circuit structures.

FIG. 10 illustrates a method for evaluating the quality of structures on an integrated circuit wafer. At **1002** test structures may optionally be formed on a test wafer or on an integrated circuit (IC) wafer. The test structures may be formed on a test wafer or on the integrated circuit wafer at locations on one or more scribe lines between two or more die on the integrated circuit wafer. At **1004**, the test structures are exposed to an electron beam and an etching gas (or vapor), such as xenon di-fluoride (XeF_2). The etching gas or vapor concentration and electron beam density in the vicinity of the test structures are sufficient for the electron-beam activated etching of the test structures.

After etching the test structures are analyzed at **1006** to determine a measure of quality of the test structures. The test structures may be analyzed by using a scanning electron microscope to produce one or more images of the test structures. The scanning electron microscope (SEM) may provide the electron beam that interacts with the etching gas or vapor and the sample activating their chemical interaction. If the test structures are located on the integrated circuit wager, e.g., on scribe lines between die, the use of the highly focused beam of a scanning electron microscope limits exposure of the die to the electron beam and/or etching gas or vapor. As a result, the etching gas or vapor molecules etch the test structures but not the die.

The images generated by the SEM may be analyzed, e.g., by performing pattern recognition on the images, to determine the measure of quality. The pattern recognition may include determining a size of a void in each test structure. By way of example, the measure of quality may be a number of voids in the test structures that are greater than a predetermined minimum size. A histogram of the sizes of the voids may be created from the pattern recognition information. The histogram may be used in statistical process control of the integrated circuit fabrication process. Alternatively, the measure of quality may be an average grey level of one or more of the images. The average grey level may be empirically related to a number of test structures with unacceptably large voids. A yield loss may be determined at a location on the integrated circuit wafer from the measure of quality.

The wafer fabrication process used to form the integrated circuit structures may be adjusted at **1008** based on the measure of quality and/or statistical process control.

In embodiments of the present in invention, test structures may be formed directly on a production integrated circuit wafer. Such embodiments of the invention allow in-line quality control that can facilitate a quick response to manufacturing problems and implementation of troubleshooting without using special test wafers or losing product wafers for control and troubleshooting needs. The test structures are located such that the localized etching of the test structures with EBACE does not affect integrated circuit structures on nearby dies. FIG. 11A shows an example of a first embodiment of an apparatus for evaluating the quality of the integrated circuit structures. An integrated circuit wafer **1100** includes a plurality of die

1102. Each die includes one or more integrated circuit structures **1104**. The wafer **1100** includes one or more test structures **1106** formed on scribe lines **1108** between two or more adjacent die **1102**. Preferably, each test structure **1106** corresponds in dimensions and composition to one or more of the integrated circuit structures **1104**. For example, the integrated circuit structures **1104** may be electrical interconnects in the form of conductive or semiconductive plugs formed in holes of a particular diameter through an insulator layer between adjacent device layers. The test structures **306** may be similarly configured and fabricated by the same process used to form the integrated circuit structures. In this way, the test structures **1106** may be examined for voids or other production-related defects without unnecessarily sacrificing integrated circuit structures. In addition, information about the location of and number of defective test structures **1106** may be used to determine where on the wafer **1100** yield loss is a problem. The process can then be adjusted for subsequent wafers based on this information. Pattern recognition analysis of the test structures **1106** is particularly suitable in situations involving high cost or limited volume advanced development products.

Pattern recognition analysis of test structures **1116** etched using EBACE in conjunction with SEM may be too slow for some applications. Consequently, in alternative embodiments of the invention, test structures **1116** may be formed on a separate test wafer **1110**. The test wafer **1110** preferably uses the same starting substrate material as a production wafer. The test structures **1116** are formed using the same type of process as is used to form corresponding integrated circuit features on the production wafer. In this example, the test structures **1116** are electrical interconnects having a conductive material disposed in a hole. Performing EBACE or other etching on the test structures exposes voids **1112** in some of them. It is generally preferably that the voids be no larger than some maximum diameter **d**. SEM may be used in conjunction with pattern recognition to determine the presence and/or size of the voids **1112** in the test structures **1116**. Note that it is not necessary to test all of the test structures. One can determine a number of structures to test based on process criteria and process statistics.

FIG. 12 illustrates a method **1200** for structural modification using electron beam activated chemical etch (EBACE). At **1202** the target **101** or a portion thereof is exposed to the gas composition **117**. The gas composition is of a type that etches nearby portions of the target **101** when the gas composition **117** is exposed to the electron beam. At **1204** the electron beam is directed toward the target **101** in the vicinity of the gas composition **117**. An interaction between the electron beam and the gas composition **117** etches a portion of the target **101** exposed to both the gas composition **117** and the electron beam. At **1206** a target is structurally modified due to interaction between the electron beam and gas composition **117**.

There are a number of different techniques for structural modifications according to embodiments of the present invention. For example, as illustrated in FIGs. 13A-13B, a target **1300** may have a rough surface, which is exposed to an electron beam **1301** and gas composition **1303**. A gas composition **1303** is chosen such that target can be etched to substantial depth at chosen level **1302** due to interaction between the electron beam **1301** and gas composition **1303.** By way of example, the material of a target **101** may be silicon and gas composition **1303** may include a carbon-containing organic compound, an etchant and oxygen.

In other embodiments of the invention the modification of optical components may be conducted by adjusting an electron beam energy, an electron beam current or a scanning pattern of the electron beam from the electron beam column **102**. As the way of example, FIGs. 14A-14D illustrate the formation of a known Fresnel lens. As shown in FIG. 14A the scanning pattern of the electron beam **1401** from a beam column **1402** may be adjusted by varying a dwell time or a repetition rate of the electron beam **1401** for different regions **A**, **B**, **C** of a target **1404**. By way of example, the dwell time may be larger for deeper etching and may be shorter for shallower etching in order to create structures with different spatial features. Consequently, interaction between the electron beam an electron-beam activated gas composition **1403** and the target **1404** results in different depth of etching of regions **A**, **B** and **C** as shown in FIG. 4B. The dwell time and/or repetition rate of the electron beam may be controlled, e.g., through appropriate configuration of the code **125** running on the controller **120**. As shown in FIG. 4C, the scanning pattern may be varied in such a way as to etch two dimensional pattern **1407** in regions **A**, **B** and **C** to different depths.

To generate annular structures, such as those shown in FIG. 4C, the target **1404** may be rotated about an appropriate center of curvature during exposure to the electron beam **1401**. The dwell time and/or electron current for the electron beam may be varied as functions of radius **R** to account for variation in path length with respect to radius. For example, if etching to a uniform depth is desired, e.g., to form a flat-bottomed annular trench, dwell time and/or current may increase as radius increases in order to keep the overall electron dose substantially constant as a function of radius. Alternatively, the dose may be adjusted in a way that produces a desired etch profile. For example, if dwell time and electron beam current are kept constant as radius increases, the dose will be higher and the amount of etching greater for lower radius portions of the dose pattern. If it is desired to increase etching with radius, e.g., to produce a convex structure, the dose and/or dwell time may increase with radius to produce the desired structure.

It is noted that if the contribution of the gas composition **1403** to etching of the target **1404** by the electron beam **1401** does not vary significantly, the etching may be very finely controlled through precise control of the electron beam **1401**. To keep the contribution of the gas composition **1403** to the etching from varying significantly the scanning pattern of the electron beam **1401** may be adjusted for different regions of the target **1404**, e.g., by varying dwell time and/or repetition rate without varying the gas composition **1403**. As used herein varying the gas composition **1403** may include, but is not limited to varying stoichiometric ratios and/or flow rates, etc for gases making up the gas composition **1403**.

As shown in FIG. 4D, the scanning pattern of the electron beam **1401** may vary as a function of depth. For example, etching the target **1404** to a sufficient depth may form a feature having one or more sidewalls **1406** of specific shape or angle. If the scanning pattern remains more or less unchanged as a function of depth, the etching of the target **1404** tends to attack the sidewall **1406** resulting in uncontrolled slanted sidewall, as indicated by the dashed-dotted line. To avoid this effect the scanning pattern of the electron beam **1401** may be varied as a function of etch depth **d** to produce a sidewall of specific shape (i.e., a sidewall that is substantially perpendicular or has a definite angle to a plane of the target **1404**). By way of example, a width **w** of the scanning pattern may be varied as a function of depth of etching of the target **1404**. The scan width **w** may be defined as a range of excursion of the electron beam **1401** along a direction parallel to a plane of the target. For example, if the target plane is more or less horizontal, the scan width **w** may be a horizontal range of excursion of the electron beam **1401**. The horizontal range of excursion of the electron beam **1401** may be adjusted, e.g., through appropriate control of the scanner **106** with the scanner driver **108**. To fabricate the sidewall **1406** such that it is substantially vertical or has definite angle, the scanning pattern of the electron beam **1401** may be varied as a function of time such that the scan width **w** narrows as a feature is etched more deeply into the target **1404**.

Finally, as may be seen from FIGs. 14A-14D, the combination of parametrical and spatial control of the electron beam may result in three dimensional optical component formation, for example a Fresnel lens.

Another example of structural modification using scanning pattern of the electron beam varied as a function of depth shown on FIG. 14A is to fabricate diffractive optical structures such as gratings as shown on cross-sections in FIG. 15 and in top views in FIG. 16. Such structures can be formed on a wafer **1504** with the described above technique followed by trimming the devices to required length and width. Due to the advantages of disclosed EBACE method, i.e. precise parametrical and spatial control of the electron beam, those structures can be fabricated of various shapes: sine (FIG. 15 part A and FIG. 16 part A), square (FIG. 15 part B and FIG. 16 part B), triangle (FIG. 15 part C and FIG. 16 part C), sawtooth (FIG. 15 part D and FIG. 16 part D) or otherwise.

Disclosed EBACE structural modification method can be applied to fabricate devices such as fin FETs, overcoming many disadvantages of the prior art and specifically of known method of Focused Ion Beams (FIB). Thus the system shown on FIG. 1 and EBACE method of precise structural modifications illustrated on FIG. 15 and FIG. 16 provide the ability to form fin FET devices from bulk wafers by means of selective etching/deposition as shown on FIGs. 17A-17C as cross-sectional side views of semiconductor structures. Specifically, an exemplary bulk wafer **1700** with a hardmask blocking layer **1704** and hardmask cap layer **1702** is shown on FIG. 17A. The wafer portion and both covering hardmask layers can be selectively patterned and etched to form fin structure as shown on FIG. 17B. Consequently, wafer portions between fins and sidewalls of the fins are covered with isolation layer by means of oxidation process. Since the oxide layer is much thicker on the etched substrate between the fins than on the fin’s sidewalls after removing unwanted oxide with thickness equal to sidewall’s layer some oxide isolation may remain on the substrate between the fins. The thickness of the oxide layer may be controller with EBACE or, alternatively, using FIB. Finally a fin FET device can be completed by adding insulator layers **1710** to each side of the fins and opposing end walls of the fins followed by gates formation **1706** deposited over fins insulator and oxide layers **1708** between fins as illustrated by FIG. 17C. The advantages of EBACE method over FIB are as following. Use of the EBACE method facilitates the formation of fin FET devices from bulk semiconductor wafers without changing impedances for structures thinner than 32 nm, which can happen when such devices are fabricated using

FIB methods. Additionally, EBACE method does not implant ions while FIB method does. Finally, unlike FIB, the EBACE method does not tend to smear photoresist. Furthermore migration of ions can damage equipment.

Another example of structural modification using scanning pattern of the electron beam varied as a function of depth shown on FIG. 14A is to build complex optical structures known in optical lithography as phase-shift masks (PSM). On FIG. 18A is shown an example of Alternating PSM (AltPSM) fabrication from clear quartz wafer **1800** by means of etching trenches **1806** for 180 degrees phase shift leaving areas **1804** with 0 degrees phase shift. Chrome lines **1802** do not allow the light to go through. As the phase goes from positive to negative, it passes through 0. The intensity (proportional to the square of the phase) also goes through 0, making a very dark and sharp line on the wafer. Thus a resist pattern similar to mask pattern, schematically shown on FIG. 18B in a way of example, remains after development. The cross-section on FIG. 18A is made along the S1-S2 dashed line indicated. As known, the AltPSM must be accompanied by a second "trim" mask, resulting in extra cost and decreased stepper throughput. The trimming process can be done using EBACE method.

The disclosed EBACE method can be used to correct defects in devices and components with significant reduction of fabrication costs since it combines two processes simultaneously – etching and imaging. Fabrication process quality can be achieved by minimization of difference between known defects in fabricated device and ideal device. This reduction can be done by iterative etching and imaging of existing defects.

Another advantage of EBACE method is that it can be used for strain reduction or isolation by etching strain relief trenches.

Another alternative embodiment of the present invention relates to patterning of certain metals that cannot be etched by conventional techniques. Such embodiments may be employed e.g., in fabrication of integrated circuit devices that use copper for electrical interconnections. Copper is generally a better conductor than aluminum. Consequently copper metal components can be made smaller that aluminum components and will require less energy to pass electricity through them, which leads to better processor performance. Because copper does not easily form volatile compounds, copper can not be patterned by photoresist masking and etching techniques and/or by EBACE, as may be done with aluminum. Instead an additive patterning process is used. In this process, an underlying silicon oxide insulating layer is patterned with open trenches where the conductor should be. A thick coating of copper that significantly overfills the trenches is deposited on the insulator, and Chemical-Mechanical Polishing (CMP) method is used to remove the copper to the level of the top of the insulating layer. Copper sunken within the trenches of the insulating layer is not removed and becomes the patterned conductor.

In an embodiment of the present invention the EBACE method may be combined with selective ion implantation for patterned etching of materials that are otherwise difficult to etch. The ion implantation may be performed either with or without using a mask. For example, as shown in FIG. 19A a wafer **1902** may be covered by a copper layer **1904** with an insulator layer **1906** on the top. The insulator layer **1906** can be etched by means of interaction of electron beam **1401** from a beam column **1402** with gas composition **1403** to form trenches in the insulator layer **1906** using EBACE as shown in FIG. 19B. The trenches expose portions of the copper layer **1904**. Alternatively, the mask pattern may be formed using conventional photolithographic techniques. Once the mask is formed, exposed portions of the copper layer **1904** are subjected to bombardment by energetic ions **1908** to create volumes **1910** of volatilizable material beneath the trenches as illustrated in FIG. 19C. For example, the energetic ions **1908** may be oxygen ions. Implanting sufficient doses of oxygen ions into the copper layer **1904** can form volumes **1910** of copper oxide. Where a mask is used, the ion bombardment may take place over a wide area. In alternative embodiments, ions may be implanted at selected locations without using a mask. For example, a focused ion beam system may be used to directly "write" a pattern of ion implantation at selected locations on the copper layer **1904**. Furthermore, embodiments of the invention may be implemented using combinations of ion bombardment through a mask and direct write (e.g., focused beam) ion implantation. Alternatively, ions may be implanted using an ion diffusion top layer deposition tool.

The depth of ion implantation may be controlled, e.g., by control of the ion energy. Oxygen implantation depths for energies between about 20-50 kV have been reported for implantation of oxygen ions into copper to depths of about 200 nm to about 300 nm. The copper oxide volumes **1910** may be etched using EBACE method to form a desired pattern on a wafer shown on FIG. 19D. By way of example, and without limitation, a gas composition used to etch copper oxide volumes **1910** may include a chlorine-based etching compound, e.g., Cl_x-F_x. The electron beam may be provided by a wide area "flood" gun, e.g., a 300-mm electron flood gun. The smoothness of the bottom of the etched structure has been determined to be largely dependent on the oxygen ion dose (e.g., in terms of the number of ions implanted per unit area). Generally, a higher dose produces a smoother bottom to the etched structure. In experiments, structures 200 nm to 300 nm deep have been formed in copper with 1 nm root mean square (rms) bottom uniformity using a combined oxygen ion implantation and EBACE technique. Experiments were performed using an oxygen ion energy of about 300 electron volts and an ion dose of about 10^{15} ions/cm^2.

It is noted that rotationally symmetric patterns may be etched using the above ion implantation and EBACE technique by rotating the target substrate about an axis during ion implantation using a focused ion beam. The ion dose may be varied as a function of radius to obtain a desired dose profile with respect to radius. In addition, ion energy may be varied with respect to radius to produce a desired etch pattern with respect to radius.

A method for 3-D image reconstruction using electron beam activated chemical etch (EBACE) is disclosed. A target or portion thereof may be exposed to a gas composition of a type that etches the target when the gas composition and/or target are exposed to an electron beam. By directing an electron beam toward the target in the vicinity of the gas composition, an interaction between the electron beam and the gas composition etches a portion of the target exposed to both the gas composition and the electron beam. De-layering etching of the target due to interaction between the electron beam and gas composition may be combined with real time imaging of each layer of structure. Those images can be retained in database for further 3-D image reconstruction of the target.

In some embodiments the system **100** may optionally include a tilt column **113**, as shown in FIG. 20. The tilt column **113** is essentially a scanning electron microscope (SEM) beam column that is tilted at an angle α with respect to the surface of the target **101**. The tilt column **113** may include an electron source, beam optics an immersion lens configured as in the beam column **102**. The tilt column **113** may obtain SEM images of the target **101** at a viewing tilted angle α.

FIG. 21 illustrates a method **2100** for target de-layering using electron beam activated chemical etch (EBACE). At **2102** the target structure **103** or a portion thereof is exposed to the gas composition **117**. The gas composition is of a type that etches nearby portions of the target **101** when the gas composition **117** is exposed to the electron beam. At **2104** the electron beam is directed toward the target **101** in the vicinity of the gas composition **117**. An interaction between the electron beam and the gas composition **117** etches a portion of the target **101** exposed to both the gas composition **117** and the electron beam. At **2106** the target structure **103** is de-layered by means of etching due to interaction between the electron beam and gas composition **117** is enhanced. At **2108** each layer of etched target structure is imaged in real time and stored in a database **133** on mass storage device **132** (or in memory **124**). The database **133** may be optimized to remove replicated layers in order to save storage space without loss of structural information. At **2110** images of each layer of the targeted structure **103** can be retrieved from the database **133** for 3-D image reconstruction analysis.

FIGs. 22A-22B, illustrate a 3-D example of 3D image reconstruction of the target structure **103** from images of different layers of the target structure **103**. These images may be stored in the database **133**. In this example illustrated in FIGs. 22A-2B, the target structure **103** is a portion of a semiconductor device having a double-gated fin FET structure. Images of target structure layers **2202** may be stored in the database **133**. The images are schematically shown in a form of frames **2204**. The frames **304** may be obtained sequentially at regular intervals in a top-down fashion as the EBACE process etches deeper into the target structure **103**. The images may be compressed and scaled in dimensions X and Y and positioned in dimension Z so that a 3-D image **2200** of target structure **103** can be reconstructed using known methods, e.g. interpolation, without loss of structural information as illustrated in FIG. 3B. For example, each frame **2204** may be regarded as a 2-dimensional image of a slice or cross-section of the target structure **103** within a portion of the target substrate **101**. A relative depth may be determined for each frame **2204** and the 3-D image **300** may be reconstructed from the 2-D cross-sectional information in each frame and a relative depth between two or more frames. The reconstruction process may be visualized as a sequential stacking of the frames **2204**. The depth of each frame may be estimated from if the distance between the tope of the feature (imaged in a top frame) and a bottom of the feature (imaged in a bottom frame). For example, if the depth between the top and bottom of the feature is D and there are N images, the distance ΔD between adjacent images may be estimated as $\Delta D = D/N$. By way of example, the depth D may be determined from an image of the feature taken with the tilt column **113**. From the image, a distance d between the top of the feature and the bottom of the feature may be measured on the image. This measurement gives the distance in the plane of the image. If the tilt angle α is known, the distance along the image may be converted to a depth from simple trigonometry, e.g., by dividing the measured distance d by the cosine of the tilt angle α. Alternatively, the depth D may be estimated from a known etch rate for the EBACE process and a known time between the first (top) and last (bottom) frames. In addition, the depth D may be directly measured, e.g., using an atomic force microscope.

There are a number of commercially available software packages for obtaining the 3-D image **2200** from the stack of 2-D images in the frames **2204**. For example, Amira software from Mercury Computer Systems Inc. of Chelmsford, Massachusetts may be used to generate the 3-D image from a stack of 2-D images. The obtained 3-D image **2200** can be analyzed for the presence of possible random or systematic defects in the structure **103** or for other structural analysis purposes. The 3-D image **2200** is also useful for making 3-D measurements, e.g., of a volume or surface area of a three-dimensional feature.

Embodiments of the present invention have certain advantages over prior art techniques for generating 3D images of buried structures. For example, one prior art 3D image technique uses a focused ion beam (FIB) system to remove layers of material. After each layer is removed, a separate imaging system (e.g., a SEM), obtains an image of the target. The 3D image is built through a sequence of FIB and imaging. Unfortunately, this process can be relatively slow, since FIB de-layering and SEM imaging cannot be done simultaneously. The slow rate of imaging makes it difficult to monitor and adjust the de-layering process. In addition, removal of target structure layers by FIB may tend to smear or damage structural features, making the resulting 3D image a less than reliable representation of the actual target structure.

Embodiments of the present invention, by contrast use the same electron beam and the same tool to do both EBACE and target imaging. As a result, images may be obtained very quickly and the progress of the etching may be monitored in real time as it happens. Furthermore, EBACE is less likely to smear or damage features of the structure **103B** while obtaining the frames **2204** containing images of the layers **2202** of the target structure **103**.

While the above is a complete description of the preferred embodiment of the present invention, it is possible to use various alternatives, modifications and equivalents. Therefore, the scope of the present invention should be determined not with reference to the above description but should, instead, be determined with reference to the appended claims, along with their full scope of equivalents. Any feature, whether preferred or not, may be combined with any other feature, whether preferred or not. In the claims that follow, the indefinite article “A”, or “An” refers to a quantity of one or more of the item following the article, except where expressly stated otherwise. The appended claims are not to be interpreted as including means-plus-function limitations, unless such a limitation is explicitly recited in a given claim using the phrase “means for.”

WHAT IS CLAIMED IS:

1. A method for etch selectivity enhancement during electron beam activated chemical etch (EBACE), comprising:
   exposing a target or portion thereof to a gas composition, wherein the gas composition is of a type that etches the target when the gas composition and/or target are exposed to an electron beam;
   directing an electron beam toward the target in the vicinity of the gas composition, whereby an interaction between the electron beam and the gas composition etches a portion of the target exposed to both the gas composition and the electron beam; and
   enhancing a selectivity of etching of the target due to interaction between the electron beam and gas composition.

2. The method of claim 1 wherein the target includes a first region containing a first material and a second region containing a second material, wherein enhancing the selectivity of etching of the target includes converting the first material into the second material, whereby the first and second regions etch at substantially the same rate.

3. The method of claim 2 wherein the second material is an oxide of the first material.

4. The method of claim 3, wherein the first material is silicon and the second material is silicon oxide.

5. The method of claim 2 wherein the gas composition includes a carbon-containing compound, an etchant and oxygen.

6. The method of claim 5 wherein the carbon-containing organic compound is a hydrocarbon or carbon monoxide.

7. The method of claim 6, wherein the hydrocarbon is methane or ethylene.

8. The method of claim 5 wherein the etchant is xenon di-fluoride (XeF_2), nitrogen (N_2), hydrogen (H_2), water vapor (H_2O) or carbon monoxide.

9. The method of claim 1 wherein the target includes a first region containing a first material and a second region containing a second material, wherein enhancing the selectivity of

etching of the target includes covering the second material but not the first material with a third material.

10. The method of claim 9 wherein the third material reduces a rate of etching of the second material relative to the first material.

11. The method of claim 9 wherein the third material is carbon.

12. The method of claim 11 wherein the gas composition includes a carbon-containing organic compound, an etchant and oxygen.

13. The method of claim 11 wherein the carbon-containing organic compound is ethylene.

14. The method of claim 11 wherein the etchant is xenon di-fluoride (XeF_2).

15. The method of claim 1 wherein enhancing the selectivity of etching includes adjusting an electron beam energy, an electron beam current or a scanning pattern of the electron beam.

16. The method of claim 15 wherein adjusting a scanning pattern includes varying a dwell time or a repetition rate of the electron beam for different regions of the target.

17. The method of claim 15 wherein adjusting a scanning pattern includes varying a dwell time or a repetition rate of the electron beam for different regions of the target without varying the gas composition.

18. The method of claim 15 wherein adjusting a scanning pattern includes varying a width of the scanning pattern as a function of depth of etching of the target.

19. The method of claim 18 wherein varying a width of the scanning pattern as a function of depth of etching of the target includes narrowing the width of the scanning pattern as a feature is etched more deeply into the target.

20. The method of claim 1 wherein enhancing the selectivity of etching of the target includes depositing passivating material on selected portions of the target, wherein the passivating material is one that reduces a rate of etching of the target due to interaction between the electron beam and gas composition.

21. The method of claim 20 wherein the selected portions include one or more sidewalls of one or more features.

22. The method of claim 20 wherein the passivating material includes carbon.

23. The method of claim 22 wherein the gas composition includes a carbon monoxide or a carbon-containing organic material.

24. The method of claim 23 wherein the carbon-containing organic material includes a hydrocarbon.

25. The method of claim 24 wherein the hydrocarbon includes ethylene or methane.

26. The method of claim 23 wherein the gas composition includes an etchant that, upon activation by the electron beam, etches targets portions not coated with carbon.

27. The method of claim 26 wherein the etchant is xenon di-fluoride (XeF_2), hydrogen (H_2), nitrogen (N_2), water vapor (H_2O) or carbon monoxide.

28. The method of claim 26 wherein the gas composition includes an inert gas, the method further comprising ionizing at least a portion of the inert gas with the electron beam thereby producing ions, and bombarding the target with the ions.

29. The method of claim 20 wherein the gas mixture includes a reactive gas, the method further comprising reacting the reactive gas with the passivating material such that the passivating material is removed from the target.

30. The method of claim 1 wherein enhancing the selectivity of etching of the target includes embedding within the target a structure that reacts differently with the electron beam and gas composition than other nearby portions of the target.

31. The method of claim 30 wherein the material composition of the structure is selected such that the interaction between the electron beam and the gas composition etches the structure more rapidly than the other nearby portions of the target, whereby rapid disappearance of the structure serves as an endpoint indicator.

32. The method of claim 30 wherein the material composition of the structure is selected such that the interaction between the electron beam and the gas composition etches more

the structure more slowly than the other nearby portions of the target, whereby appearance of the structure serves as an endpoint indicator.

33. The method of claim 1 wherein enhancing the selectivity of etching of the target includes using a focused ion beam to remove from the target one or more materials that are not removable by etching due to the interaction between the electron beam and gas composition.

34. The method of claim 1 wherein enhancing the etch selectivity comprises including in the gas mixture one or more decontaminating gases that react with the target in such a way as to remove one or more contaminants from the target and/or prevent contamination of the target by the one or more contaminants.

35. The method of claim 34 wherein the one or more contaminants include carbon.

36. The method of claim 35 wherein the one or more decontaminating gases include oxygen.

37. The method of claim 35 wherein the one or more decontaminating gases include nitrogen (N_2), argon (Ar), xenon (Xe), or hydrogen (H_2).

38. The method of claim 34 wherein including in the gas mixture one or more decontaminating gases comprises injecting the one or more decontaminating gases in close proximity to the target with a high pressure profile proximate to an intersection between the beam of electrons and the target.

39. The method of claim 38 wherein injecting the one or more decontaminating gases in close proximity to the target includes delivering the decontaminating gases using a gas system having separate gas injection pathways for gases that would otherwise react undesirably if mixed in a single feed line.

40. The method of claim 38, further comprising generating a plasma from the one or more decontaminating gases and bombarding the target with ions from the plasma.

41. A method for evaluating the quality of structures on an integrated circuit wafer, comprising the steps of:
exposing one or more test structures to an electron beam and an electron-beam activated chemical etching gas or vapor, wherein the test structures are formed on a test wafer or on

the integrated circuit wafer at locations on one or more scribe lines between two or more die on the integrated circuit wafer, whereby the electron-beam activated etching gas or vapor etches the test structures; and

analyzing the test structures after etching to determine a measure of quality of the test structures.

42. The method of claim 41 wherein the measure of quality is a number of voids in the test structures that are greater than a predetermined minimum size.

43. The method of claim 41 wherein analyzing the test structures includes the use of a scanning electron microscope to produce one or more images of the test structures.

44. The method of claim 41 wherein exposing the one or more test structures to the electron beam includes the use of a scanning electron microscope to provide the electron beam.

45. The method of claim 44, wherein analyzing the test structures further comprises performing a pattern recognition on the images.

46. The method of claim 45 wherein performing the pattern recognition includes determining a size of a void in each test structure.

47. The method of claim 45 wherein the measure of quality is an average grey scale of one or more of the images.

48. The method of claim 45 wherein performing the pattern recognition includes determining a size of a void in each test structure and creating a histogram of the sizes of the voids.

49. The method of claim 41 wherein the test structures are on the integrated circuit wafer at locations on one or more scribe lines between two or more die on the integrated circuit wafer.

50. The method of claim 49 wherein exposing one or more test structures to an electron beam and an electron-beam activated chemical etching gas or vapor includes limiting exposure of the die to the electron beam and/or etchant, whereby the etchant etches the test structures but not the die.

51. The method of claim 41 wherein each structure includes a hole having a conductive or semiconductive material therein.

52. The method of claim 51 wherein the conductive or semiconductive material is tungsten or silicon.

53. The method of claim 52 wherein the electron beam activated etchant is xenon di-fluoride (XeF_2).

54. The method of claim 41, further comprising the step of determining a yield loss at a location on the integrated circuit wafer from the measure of quality.

55. The method of claim 41 wherein the test structures correspond in dimensions and composition to one or more structures on the integrated circuit wafer.

56. On an integrated circuit wafer having two or more die, each die having one or more integrated circuit structures, an apparatus for evaluating the quality of the integrated circuit structures, comprising:
one or more test structures formed on scribe lines between two or more adjacent die, wherein each test structure corresponds in dimensions and composition to one or more of the integrated circuit structures.

57. The apparatus of claim 56 wherein each structure includes a hole having a conductive or semiconductive material therein.

58. The apparatus of claim 57 wherein the conductive or semiconductive material is tungsten or silicon.

59. An apparatus for evaluating the quality of structures on an integrated circuit wafer, comprising:
means for exposing one or more test structures to an electron beam and an electron-beam activated chemical etching gas or vapor, wherein the test structures are formed on a test

wafer or on the integrated circuit wafer at locations on one or more scribe lines between two or more die on the integrated circuit wafer, whereby the electron-beam activated etching gas or vapor etches the test structures; and

means for analyzing the test structures after etching to determine a measure of quality of the test structures.

60. The apparatus of claim 59 further comprising means for determining a yield loss at a location on the integrated circuit wafer from the measure of quality.

61. A method for modifying a surface of a substrate (or a portion there of), comprising exposing one or more portions of the surface to a gas composition, the gas composition containing one or more gaseous components that etch the substrate upon activation by interaction with a beam of electrons; directing a beam of electrons to the one or more portions of the surface of the substrate that are exposed to the gas composition to etch the one or more portions; and modifying one or more features on the surface of the substrate by adjusting the electron beam to vary a pattern of etching of the one or more portions.

62. The method of claim 61 wherein the one or more features include one or more Fin FETs, wherein modifying the one or more features includes trimming the one or more Fin FETs.

63. The method of claim 61 wherein modifying one or more features includes changing a roughness of the substrate.

64. The method of claim 63 wherein adjusting the electron beam to vary the pattern of etching includes increasing or reducing a rate of etching of selected portions of the surface of the substrate relative to a rate of etching of other portions.

65. The method of claim 64 wherein increasing or reducing a rate of etching includes obtaining an image of the surface of the substrate and determining from the image whether to increase or reduce the rate of etching of a given selected portion.

66. The method of claim 61 wherein modifying one or more features includes fabrication of one or more optical elements on the surface of the substrate.

67. The method of claim 66 wherein the one or more optical elements include one or more lenses, Fresnel lenses or diffraction gratings.

68. The method of claim 61 wherein modifying one or more features includes forming a strain-relieving trench on the surface of the substrate.

69. The method of claim 61 wherein the substrate is a lens, wherein modifying one or more features includes changing an optical property of the lens.

70. The method of claim 69 wherein changing of the lens includes forming one or more trenches on a surface of the lens, the one or more trenches being arranged in a pattern that produces counter-defects that compensate for optical defects in the lens.

71. The method of claim 61 wherein directing a beam of electrons to one or more portions of the surface includes rotating the substrate about an axis.

72. The method of claim 71 wherein adjusting the electron beam to vary the pattern of etching includes adjusting a rate of etching of selected portions of the surface of the substrate relative to a rate of etching of other portions as a function of radius from the axis.

73. The method of claim 71, further comprising implanting ions into the one or portions of the substrate to convert the one or more portions a material that is susceptible to etching due to interaction with the electron beam and gas composition.

74. The method of claim 73 wherein the one or more portions of the substrate include copper.

75. The method of claim 74 wherein the ions include oxygen ions, whereby implanting the ions converts selected portions of the substrate from copper to copper oxide.

76. The method of claim 75 wherein the gas composition includes a chlorine-based compound selected to etch the copper oxide upon exposure of the copper oxide to the chlorine-based composition and the electron beam.

77. The method of claim 73, further comprising varying an energy of the ions to adjust a depth of the material that is susceptible to etching.

78. The method of claim 73, further comprising, adjusting a dose of the ions to vary a smoothness of a bottom of the pattern of etching of the one or more portions.

79. The method of claim 73, further comprising rotating the substrate about an axis while implanting the ions.

80. The method of claim 79, wherein implanting the ions includes adjusting an ion dose and/or ion energy as a function of radius from the axis.

81. The method of claim 73, wherein implanting the ions into the one or portions of the substrate includes forming a mask having one or more openings on a surface of the substrate and bombarding the one or more portions of the substrate through the one or more openings.

82. The method of claim 73, wherein implanting the ions into the one or more portions of the substrate includes bombarding the one or more portions of the substrate with a focused beam of the ions.

83. A method for imaging a structure, comprising:
exposing a surface of a substrate (or a portion thereof) to a gas composition, wherein the gas composition includes one or more components that etch the substrate upon activation by interaction with a beam of electrons;
directing a beam of electrons to one or more portions of the surface of the substrate that are exposed to the gas composition to etch the one or more portions;
obtaining a plurality of images of the one or more portions at different instances of time as the one or more portions are etched; and
generating from the plurality of images a three-dimensional model of one or more structures embedded within the one or more portions of the substrate.

84. The method of claim 83 wherein obtaining the plurality of images includes detecting secondary electrons generated from an interaction between the beam of electrons and the one or more portions.

85. The method of claim 83 wherein obtaining the plurality of images includes using a scanning electron microscope to detect secondary electrons generated from an interaction between the beam of electrons and the one or more portions.

86. The method of claim 83 wherein directing a beam of electrons to one or more portions of the surface includes using a scanning electron microscope to direct the beam of electrons to the one or more portions of the surface.

87. The method of claim 87 wherein obtaining the plurality of images includes using a scanning electron microscope to detect secondary electrons generated from an interaction between the beam of electrons and the one or more portions.

88. The method of claim 83 wherein directing a beam of electrons to one or more portions of the surface of the substrate and obtaining the plurality of images take place substantially simultaneously.

89. The method of claim 88 wherein directing a beam of electrons to one or more portions of the surface includes using a scanning electron microscope to direct the beam of electrons to the one or more portions of the surface.

90. The method of claim 89 wherein obtaining the plurality of images includes using a scanning electron microscope to detect secondary electrons generated from an interaction between the beam of electrons and the one or more portions.

91. The method of claim 83 wherein obtaining the plurality of images includes obtaining the images sequentially at regular intervals in a top-down fashion as the interaction between the electron beam and the gas composition etches deeper into the substrate.

92. The method of claim 83, further comprising storing the plurality of images in a database.

93. The method of claim 92 wherein generating from the plurality of images a three-dimensional model of one or more structures embedded within the one or more portions of the substrate includes retrieving images from the database and constructing the three-dimensional model from the images retrieved from the database.

94. An apparatus for imaging a structure, comprising:
a source of a gas composition adapted to expose a surface of a substrate (or a portion thereof) to the gas composition, wherein the gas composition includes one or more components that etch the substrate upon activation by interaction with a beam of electrons;

a source of electrons adapted to deliver a beam of electrons to one or more portions of the surface of the substrate that are exposed to the gas composition to etch the one or more portions;

an imaging system adapted to obtain a plurality of images of the one or more portions at different instances of time as the one or more portions are etched; and

a processor coupled to the imaging system, the processor adapted to execute one or more processor readable instructions that, when executed, generate from the plurality of images a three-dimensional model of one or more structures embedded within the one or more portions of the substrate.

95. The apparatus of claim 94 wherein the imaging system includes a secondary electron detector adapted to detect secondary electrons generated from an interaction between the beam of electrons and the one or more portions.

96. The apparatus of claim 94 wherein the imaging system includes a scanning electron microscope adapted to detect secondary electrons generated from an interaction between the beam of electrons and the one or more portions.

97. The apparatus of claim 94 wherein the source of electrons includes an electron beam column of a scanning electron microscope.

98. The apparatus of claim 97 wherein the imaging system includes a secondary electron detector of the scanning electron microscope.

99. The apparatus of claim 94 further comprising a memory operably coupled to the processor, wherein the processor and memory are adapted to store the plurality of images in a database.

100. A processor-readable medium having embodied therein processor readable instructions to be executed on a processor coupled to a gas source adapted to expose a surface of a substrate (or a portion thereof) to the gas composition, a source of electrons adapted to deliver a beam of electrons to one or more portions of the surface of the substrate that are exposed to the gas composition and an imaging system adapted to obtain a plurality of images of the one or more portions at different instances of time,

a processor coupled to the imaging system;

the processor readable instructions including one or more instructions that, when executed on the processor, cause the gas source to expose a surface of a substrate (or a portion thereof) to a gas composition from the gas source, wherein the gas composition includes one or more components that etch the substrate upon activation by interaction with a beam of electrons;

the processor readable instructions including one or more instructions that, when executed on the processor, case the source of electrons to direct a beam of electrons to one or more portions of the surface of the substrate that are exposed to the gas composition to etch the one or more portions;

the processor readable instructions including one or more instructions that, when executed on the processor, cause the imaging system to obtain a plurality of images of the one or more portions at different instances of time as the one or more portions are etched; the processor readable instructions including one or more instructions that, when executed on the processor, generate from the plurality of images a three-dimensional model of one or more structures embedded within the one or more portions of the substrate.

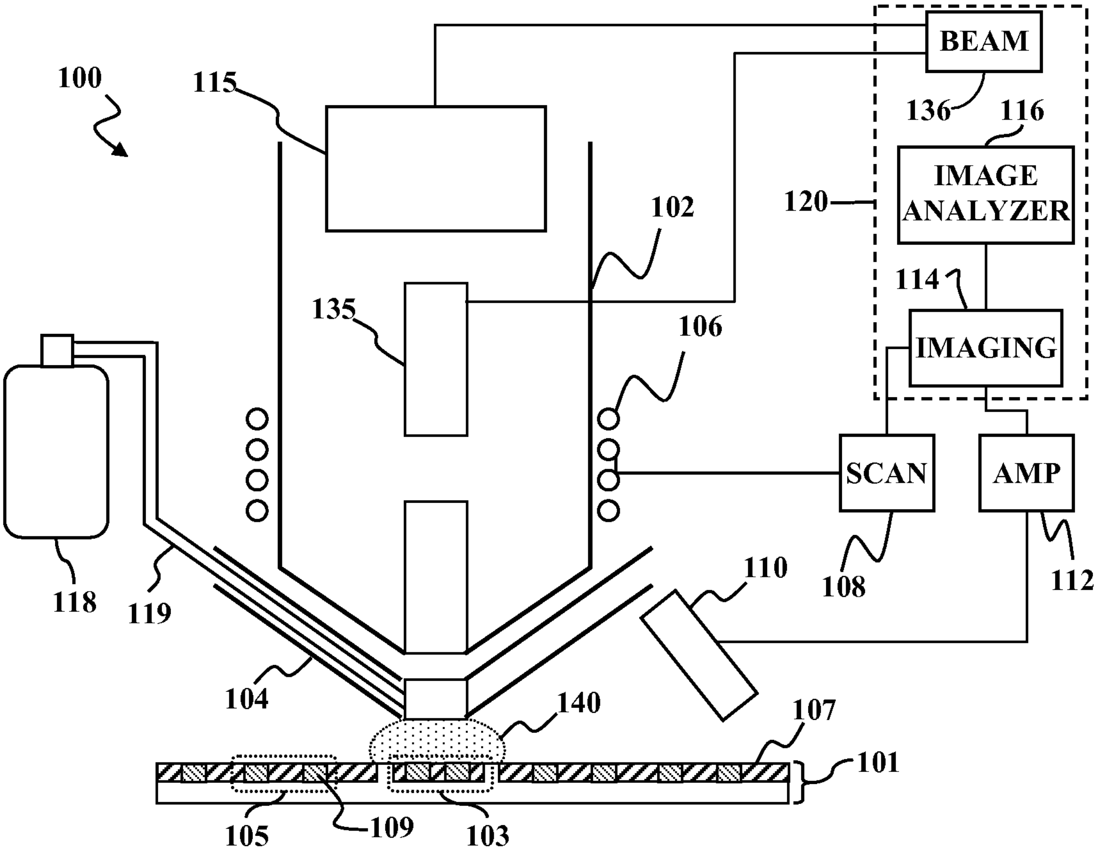
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IMAGE ANALYZER
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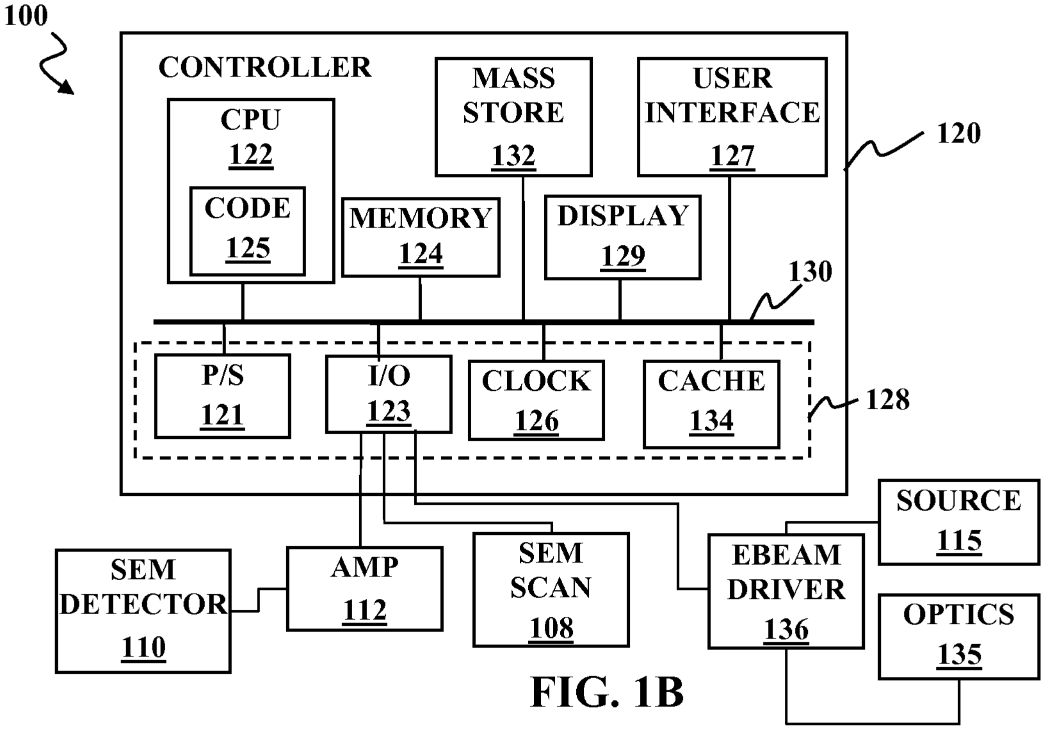
FIG. 1A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CODE 125
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USER INTERFACE 127
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MEMORY 124
DISPLAY 129
130
P/S 121
I/O 123
CLOCK 126
CACHE 134
128
SOURCE 115
SEM DETECTOR 110
AMP 112
SEM SCAN 108
EBEAM DRIVER 136
OPTICS 135

FIG. 1B

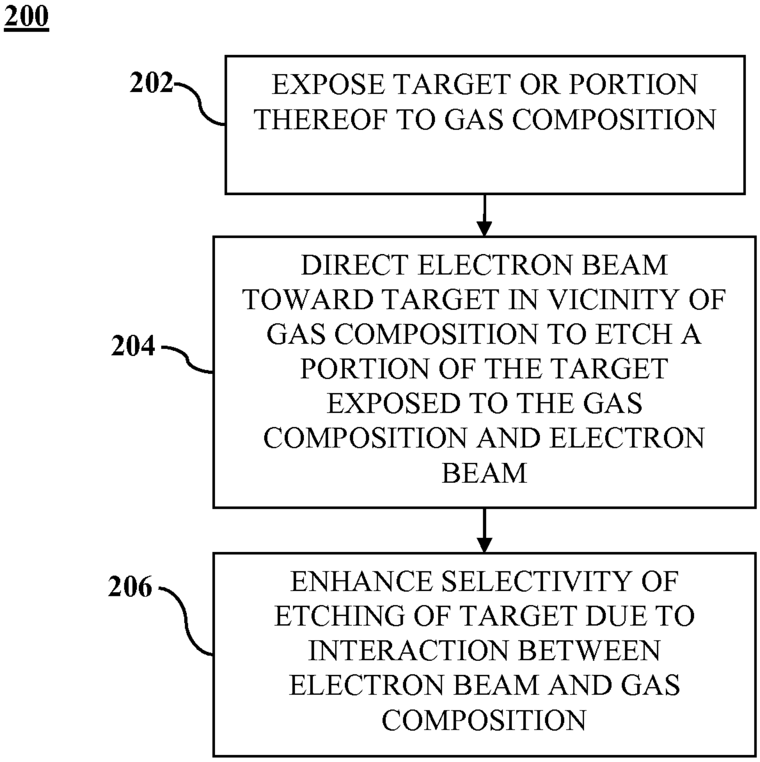

200
202
EXPOSE TARGET OR PORTION THEREOF TO GAS COMPOSITION
204
DIRECT ELECTRON BEAM TOWARD TARGET IN VICINITY OF GAS COMPOSITION TO ETCH A PORTION OF THE TARGET EXPOSED TO THE GAS COMPOSITION AND ELECTRON BEAM
206
ENHANCE SELECTIVITY OF ETCHING OF TARGET DUE TO INTERACTION BETWEEN ELECTRON BEAM AND GAS COMPOSITION

FIG. 2

FIG. 3A

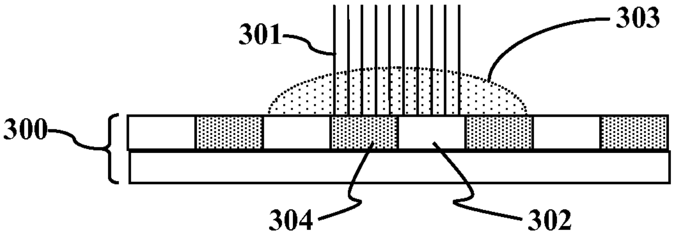


FIG. 3B

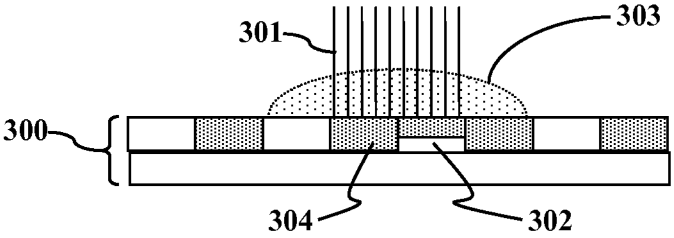


FIG. 3C

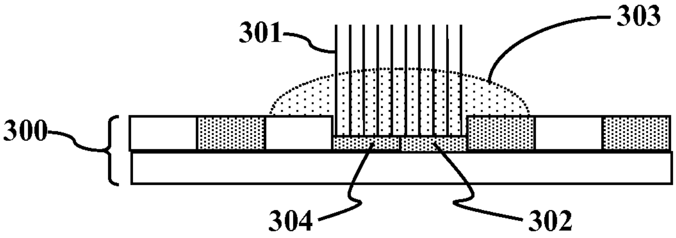


FIG. 4A

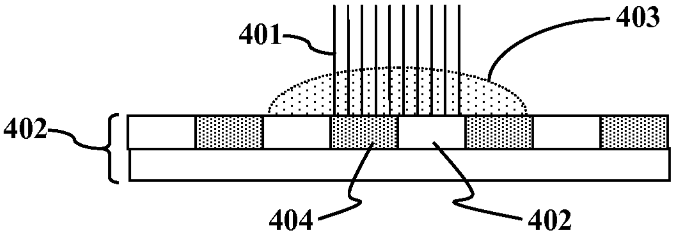


FIG. 4B

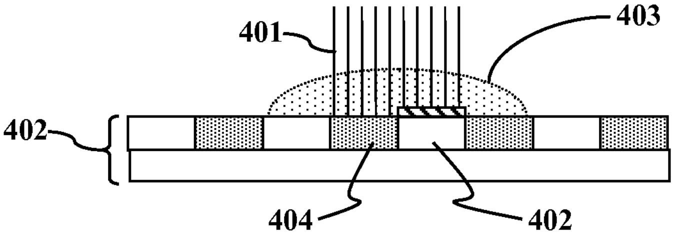


FIG. 4C

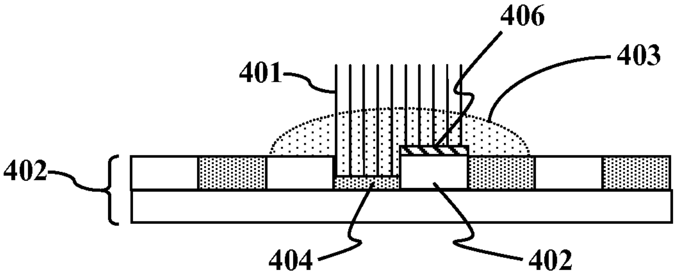


FIG. 5A

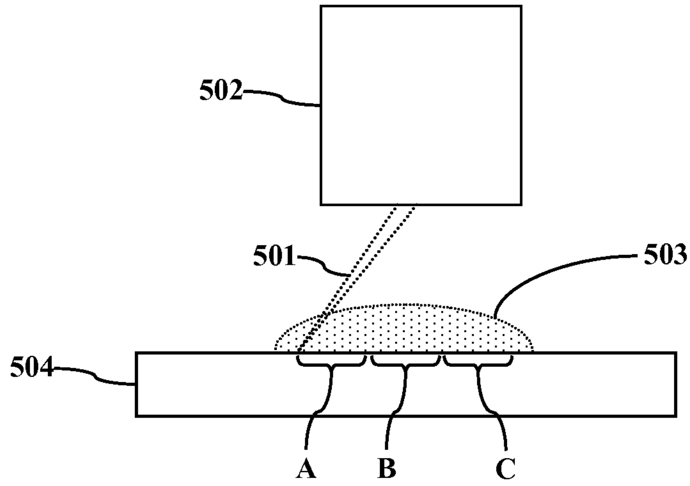


FIG. 5B

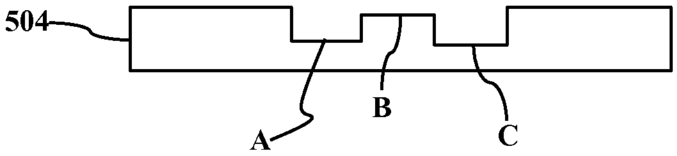


FIG. 5C

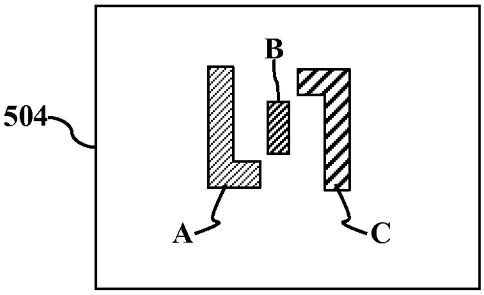
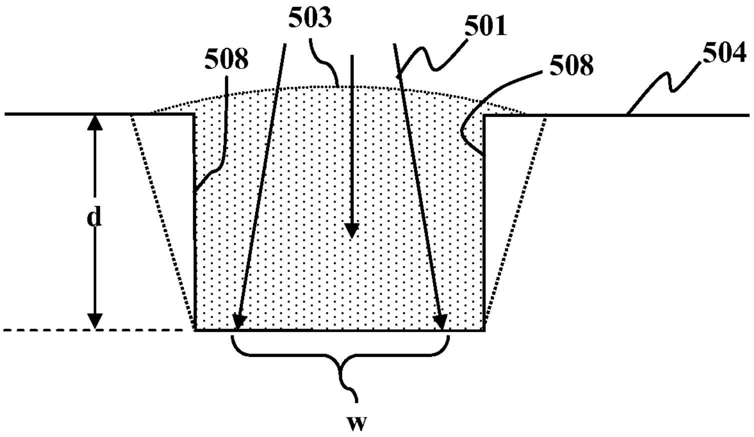


FIG. 5D



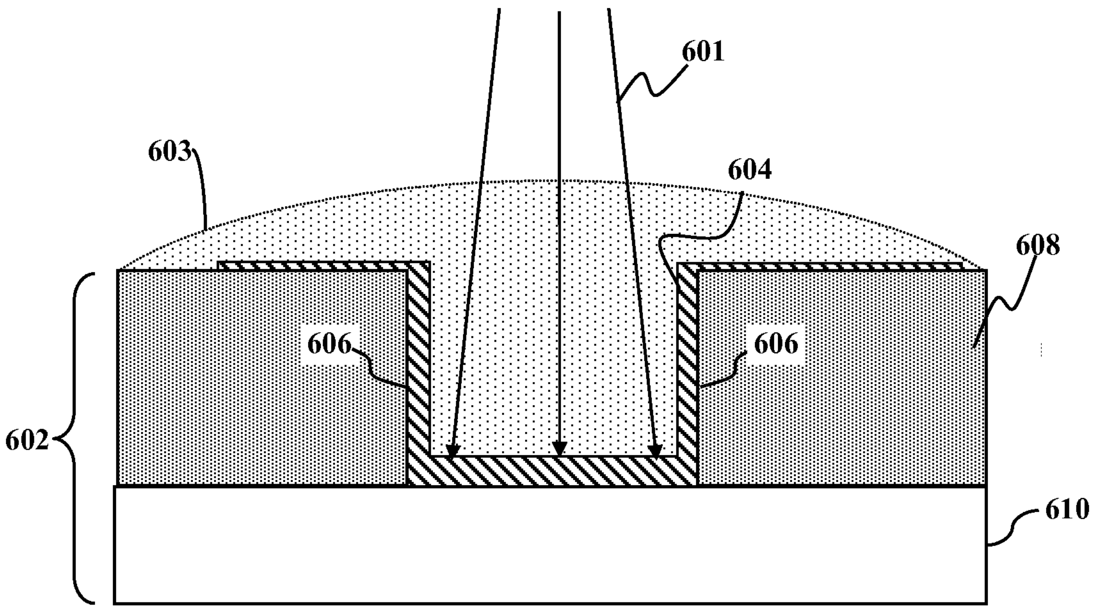


FIG. 6A

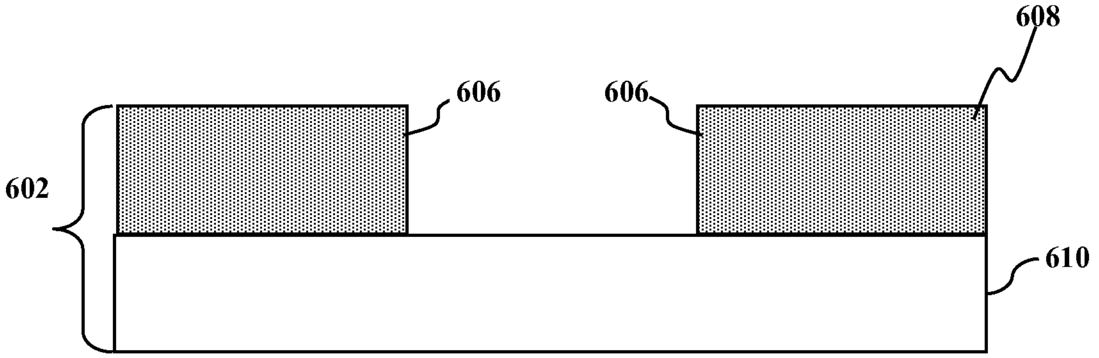


FIG. 6B

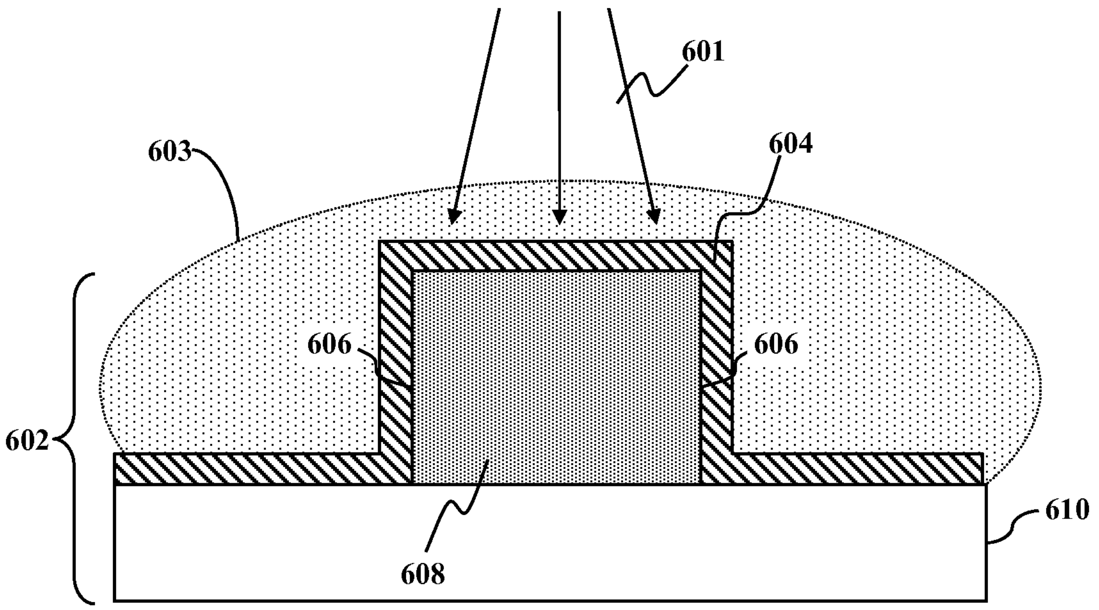


FIG. 6C

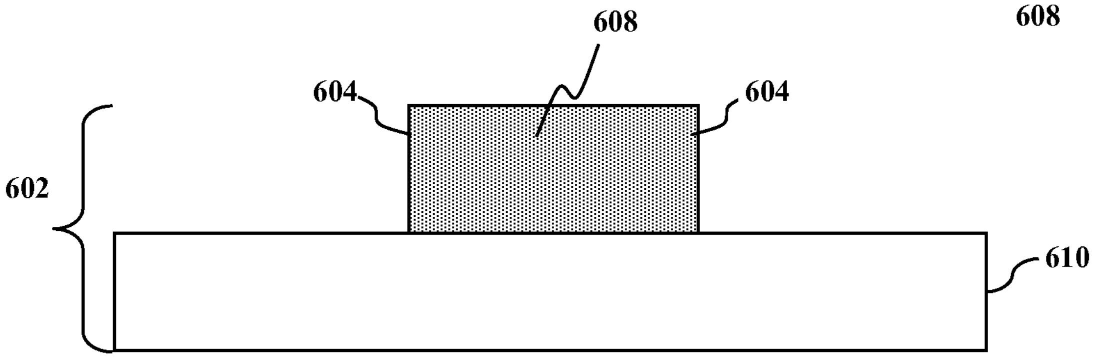


FIG. 6D

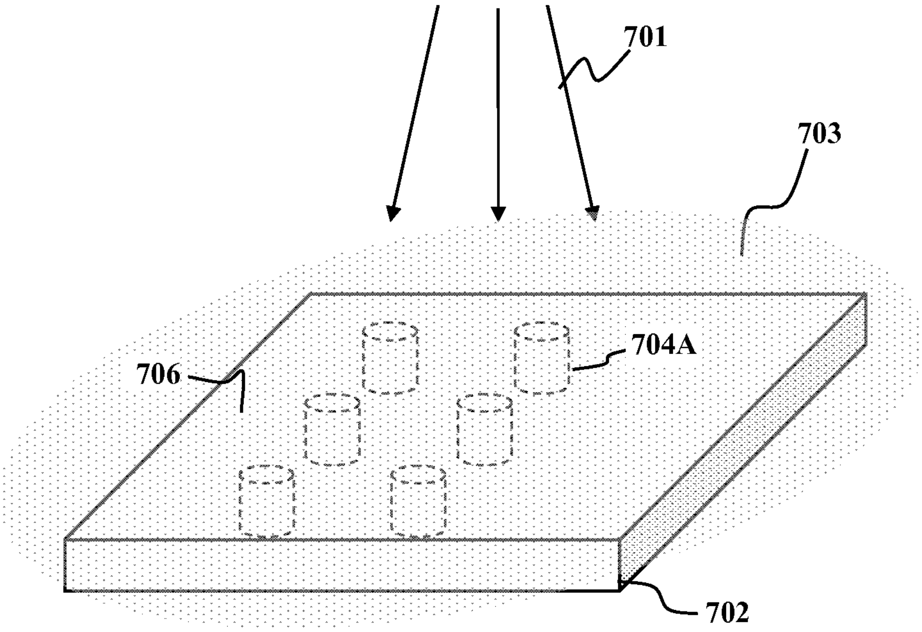


FIG. 7A

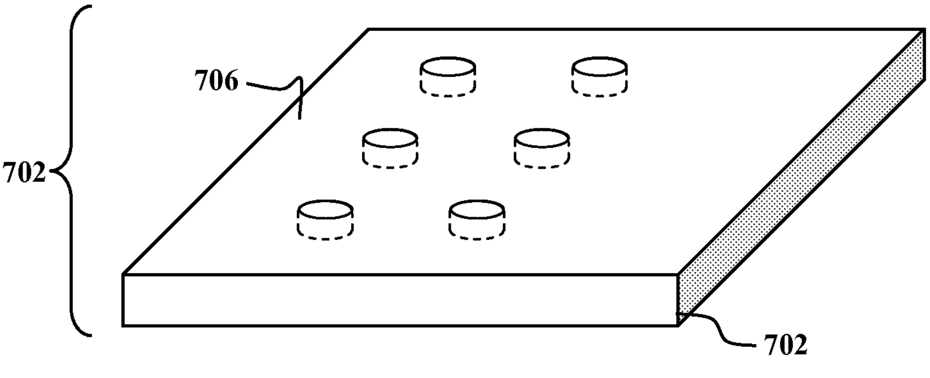


FIG. 7B

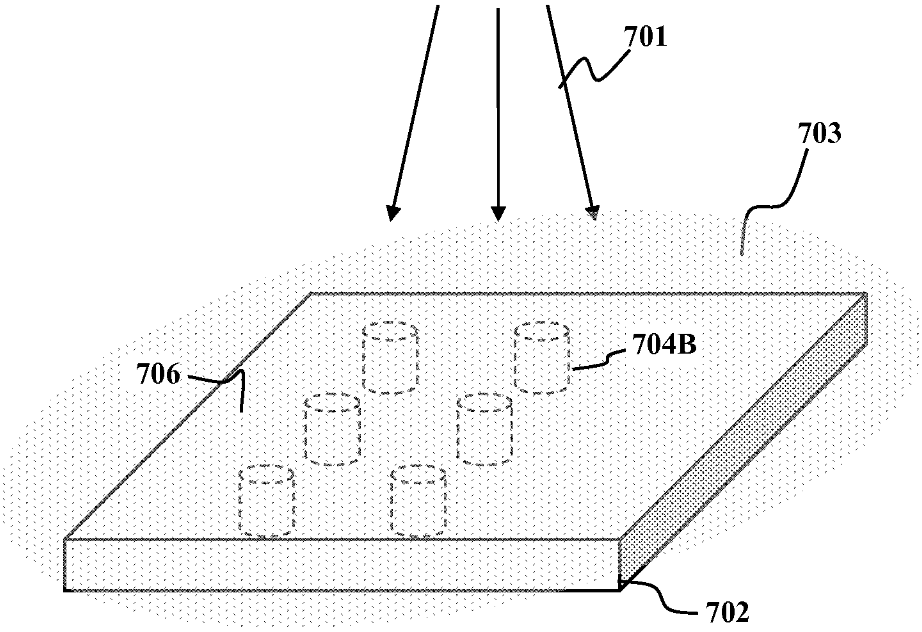


FIG. 7C

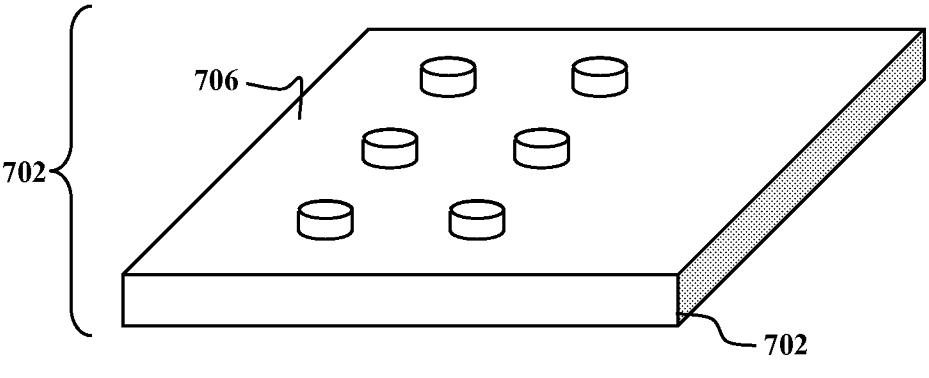
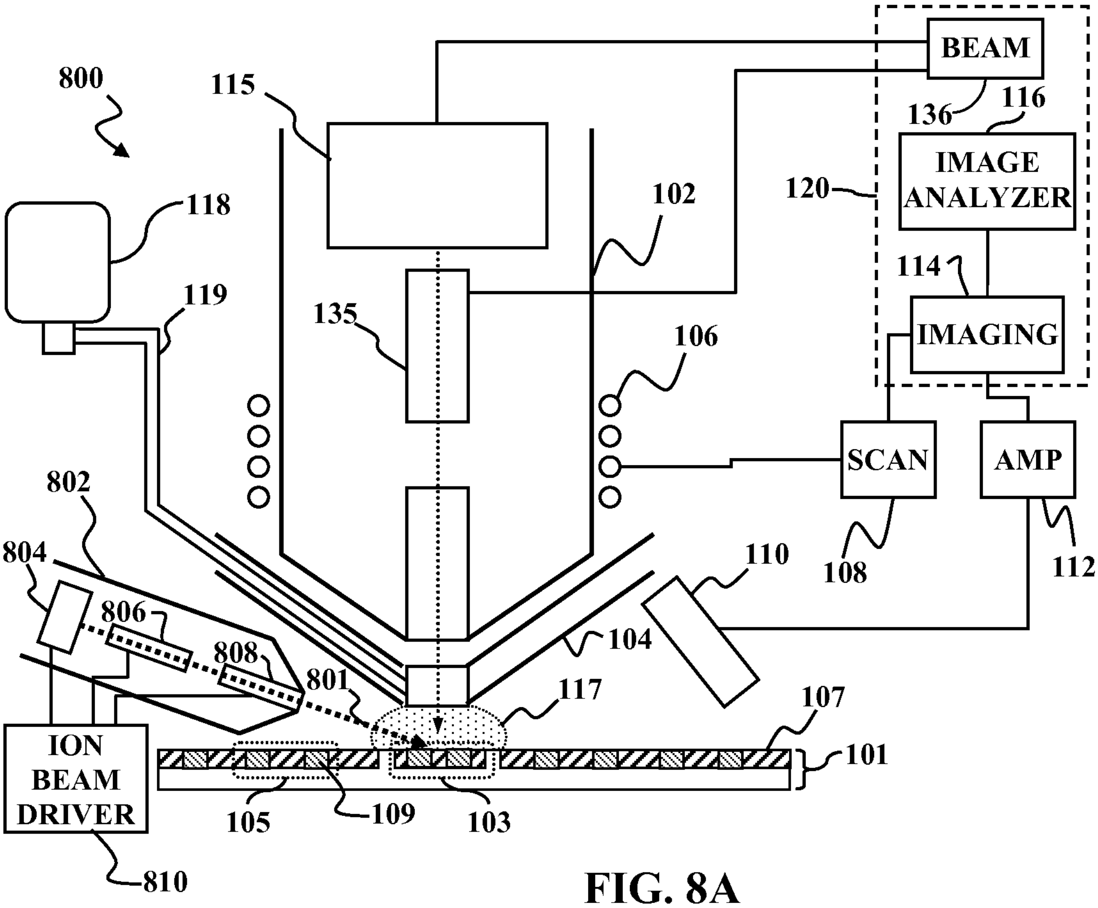


FIG. 7D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103
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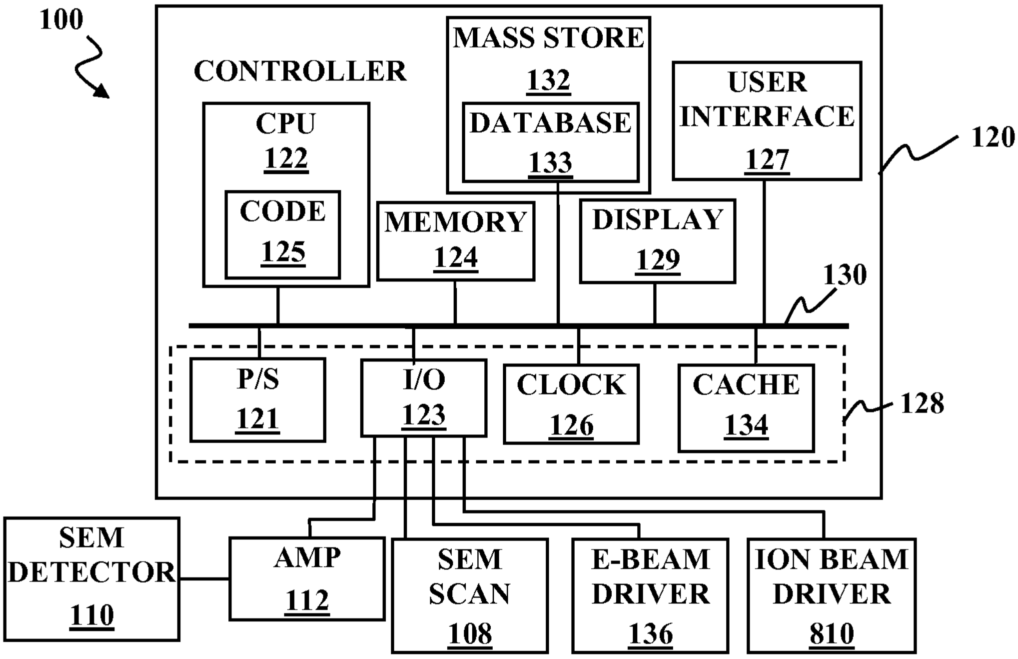
FIG. 8A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CPU 122
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MEMORY 124
DISPLAY 129
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P/S 121
I/O 123
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SEM SCAN 108
E-BEAM DRIVER 136
ION BEAM DRIVER 810

FIG. 8B

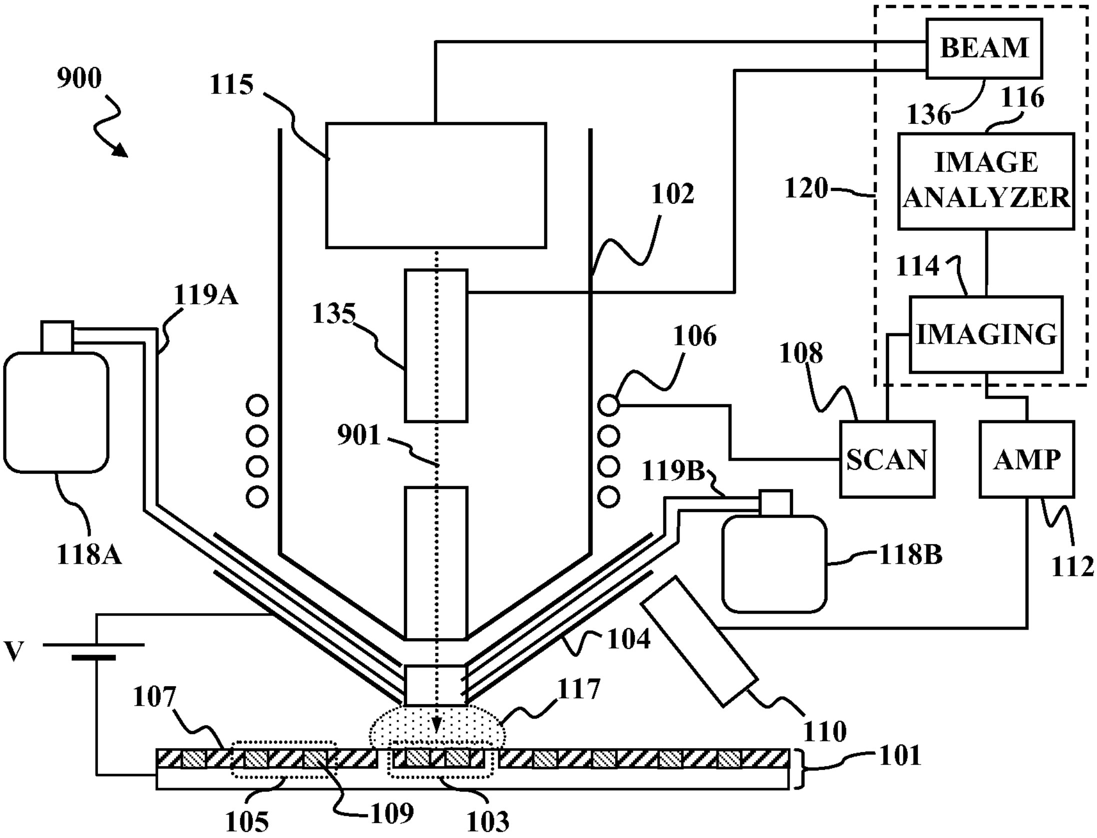
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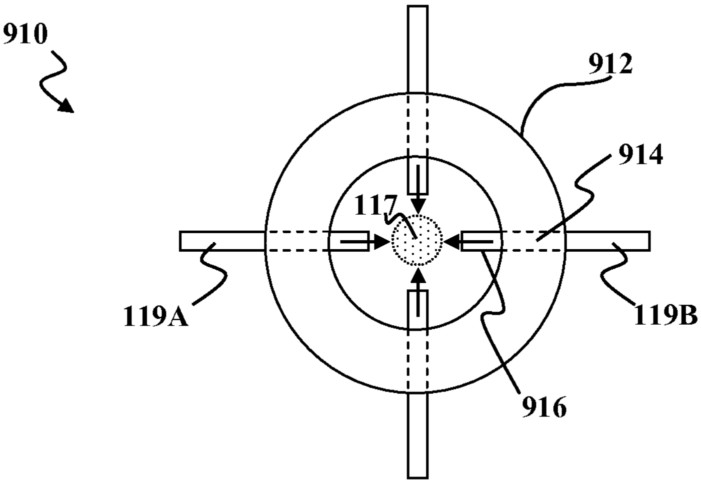
FIG. 9A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916

FIG. 9B

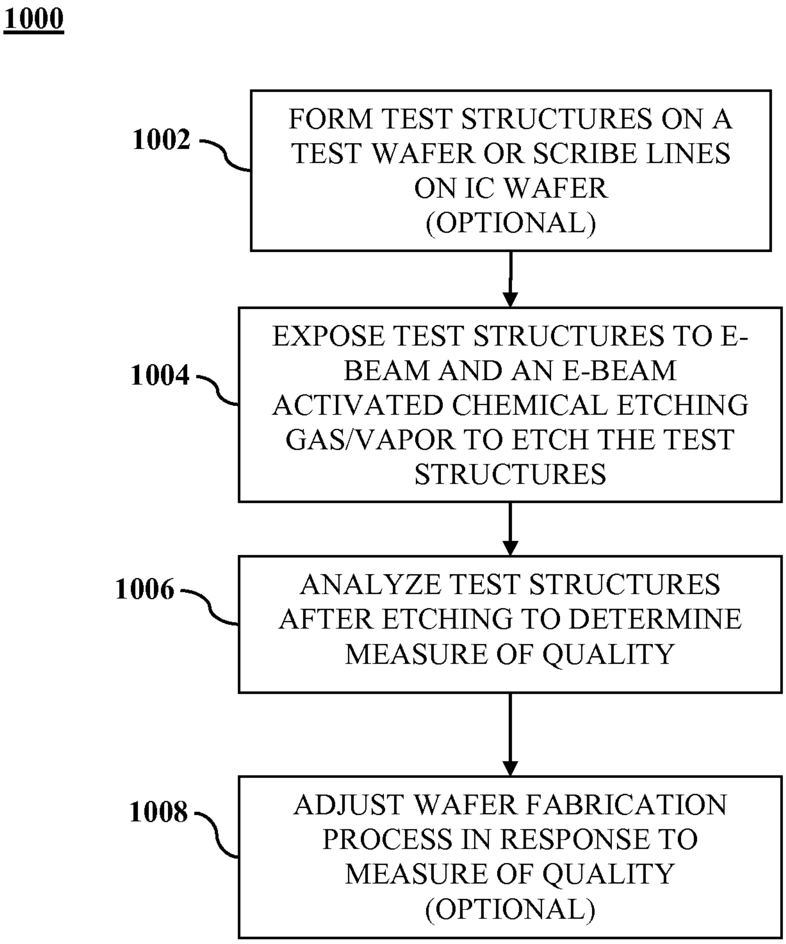

1000
1002
FORM TEST STRUCTURES ON A TEST WAFER OR SCRIBE LINES ON IC WAFER (OPTIONAL)
1004
EXPOSE TEST STRUCTURES TO E-BEAM AND AN E-BEAM ACTIVATED CHEMICAL ETCHING GAS/VAPOR TO ETCH THE TEST STRUCTURES
1006
ANALYZE TEST STRUCTURES AFTER ETCHING TO DETERMINE MEASURE OF QUALITY
1008
ADJUST WAFER FABRICATION PROCESS IN RESPONSE TO MEASURE OF QUALITY (OPTIONAL)

FIG. 10

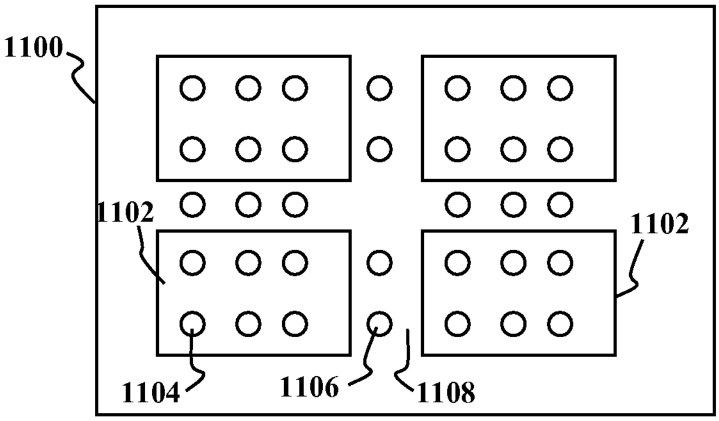


FIG. 11A

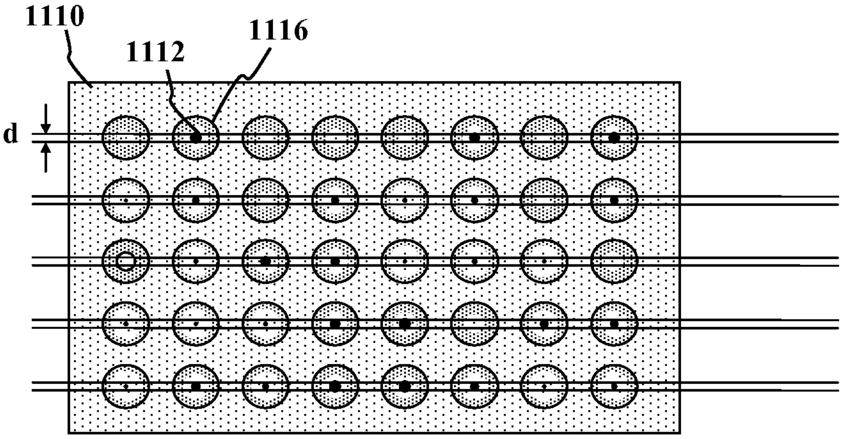


FIG. 11B

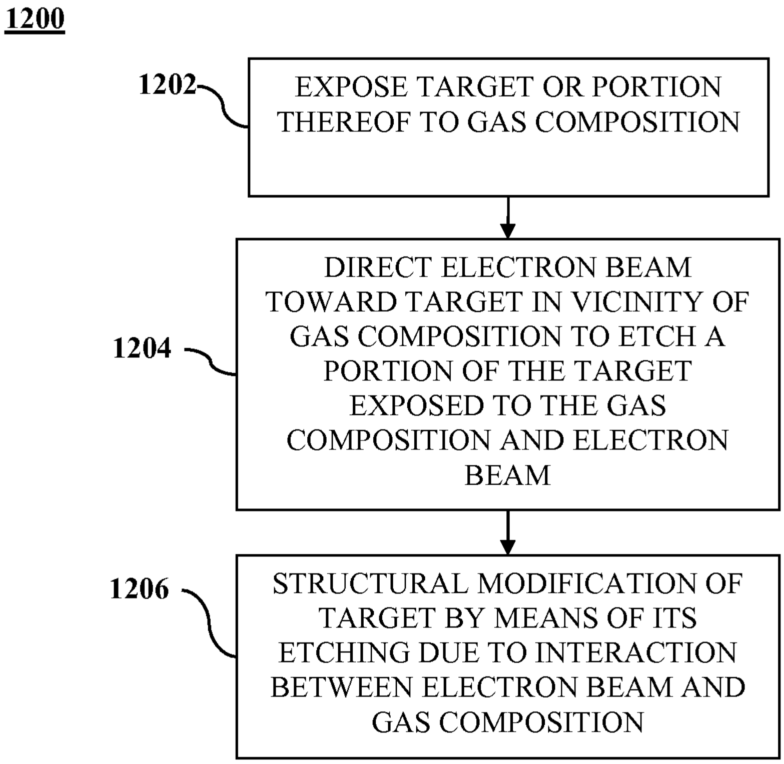


FIG. 12

FIG. 13A

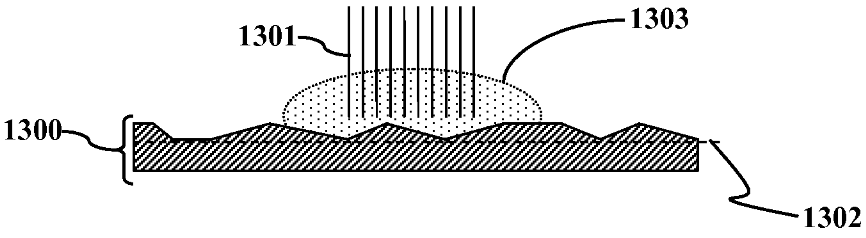
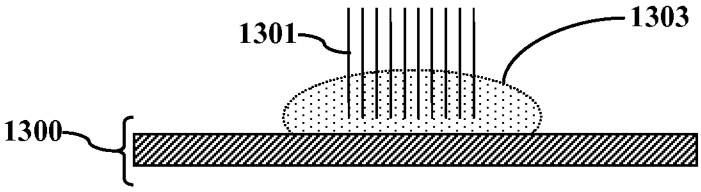


FIG. 13B



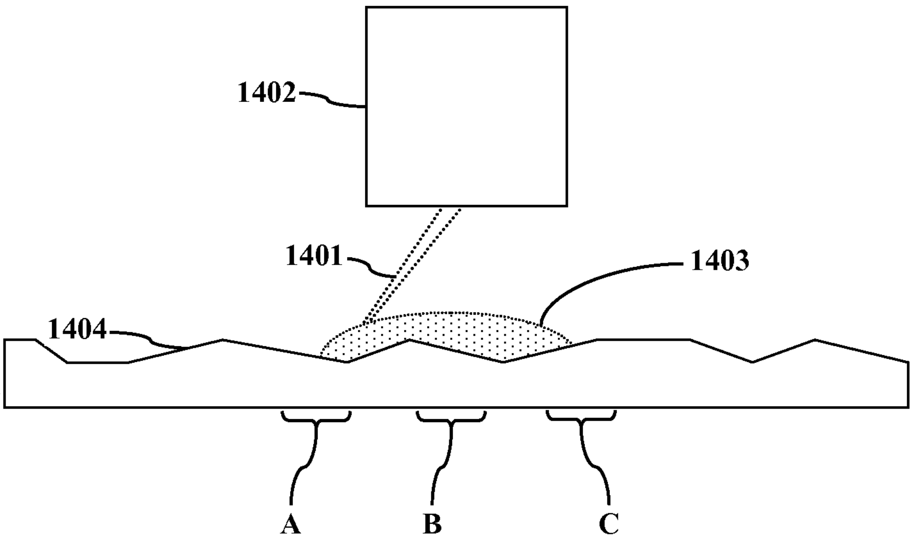


FIG. 14A

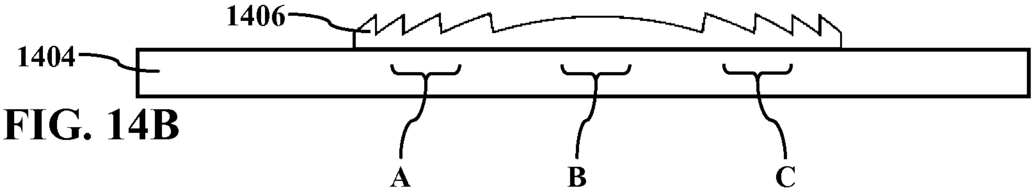


FIG. 14B

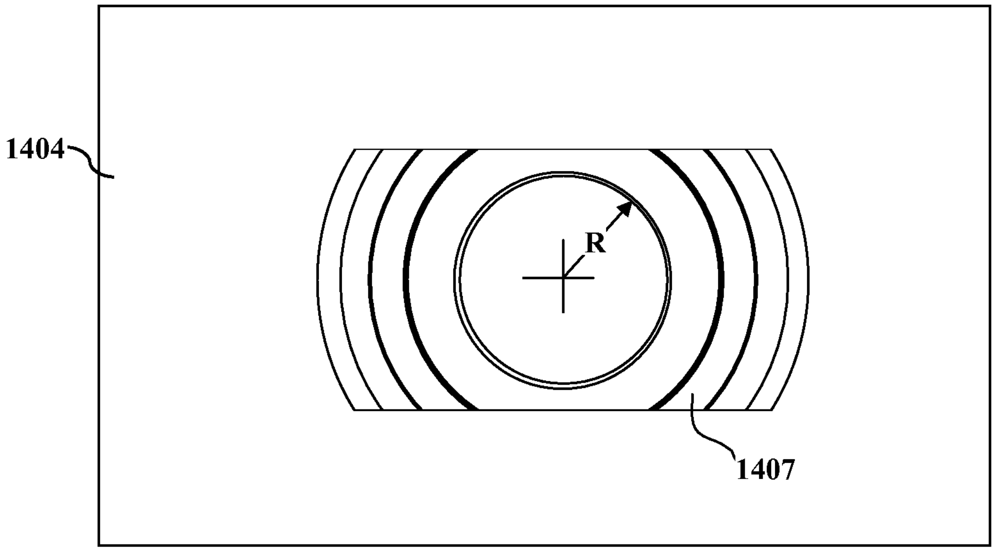
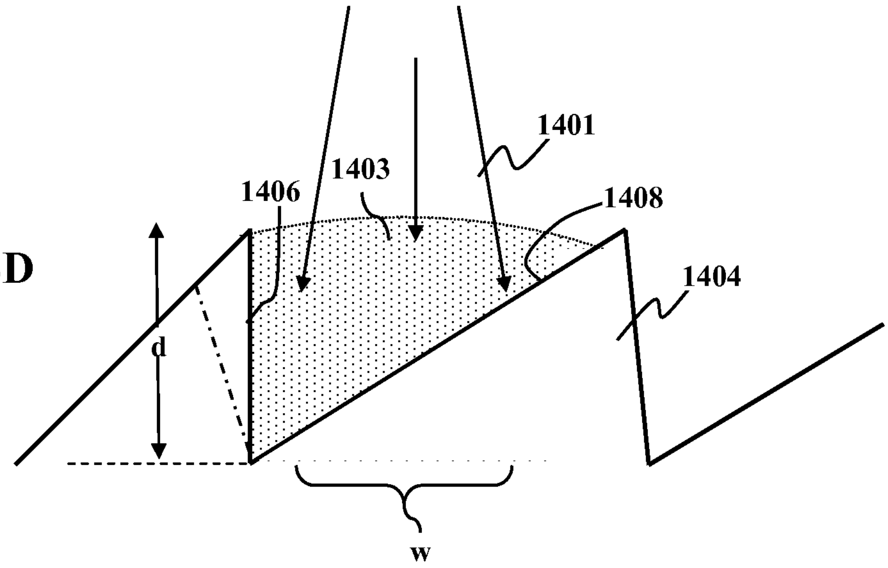


FIG. 14C

FIG. 14D



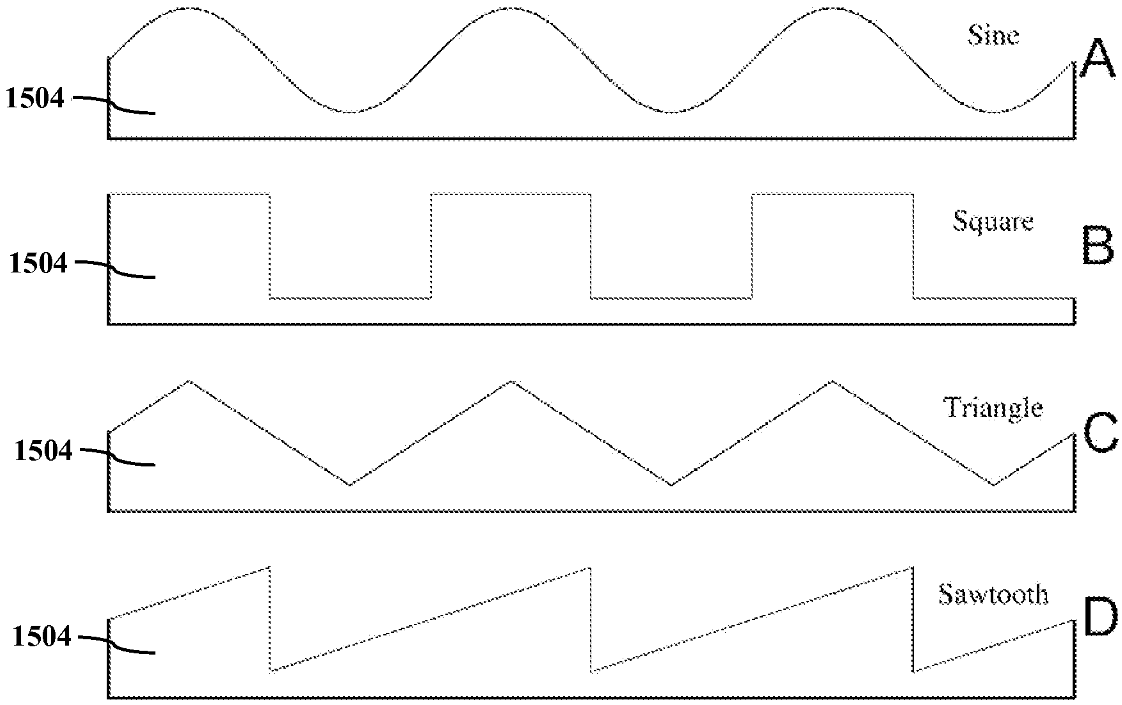

1504
Sine
A
1504
Square
B
1504
Triangle
C
1504
Sawtooth
D

FIG. 15

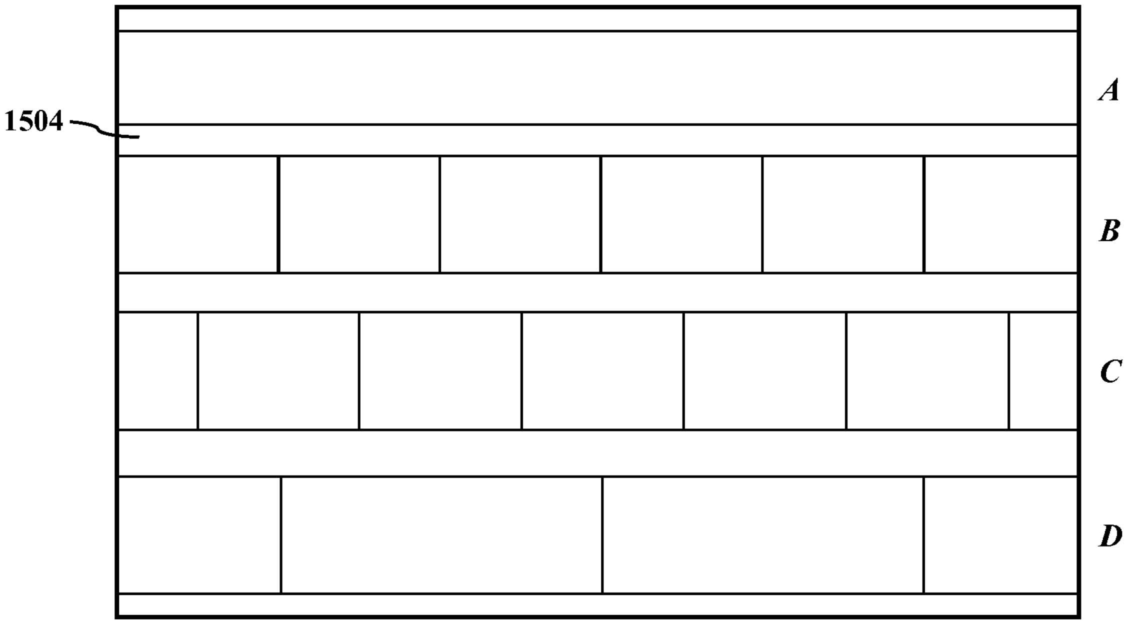

1504
A
B
C
D

FIG. 16

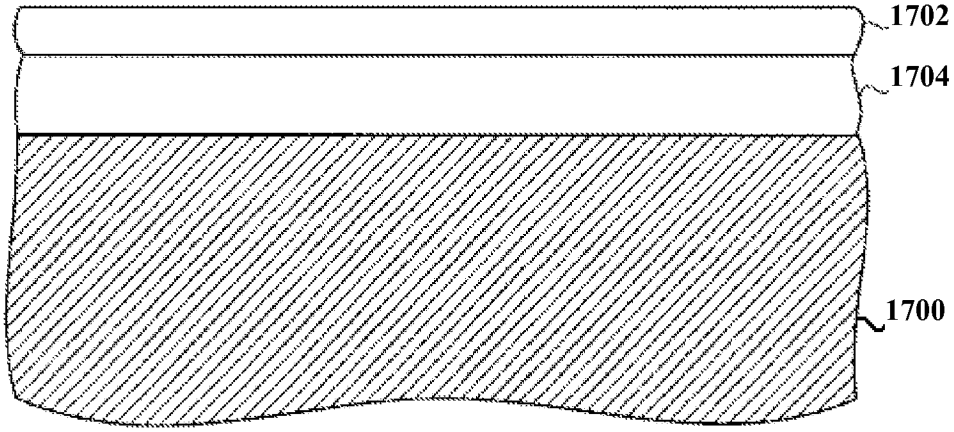


FIG. 17A

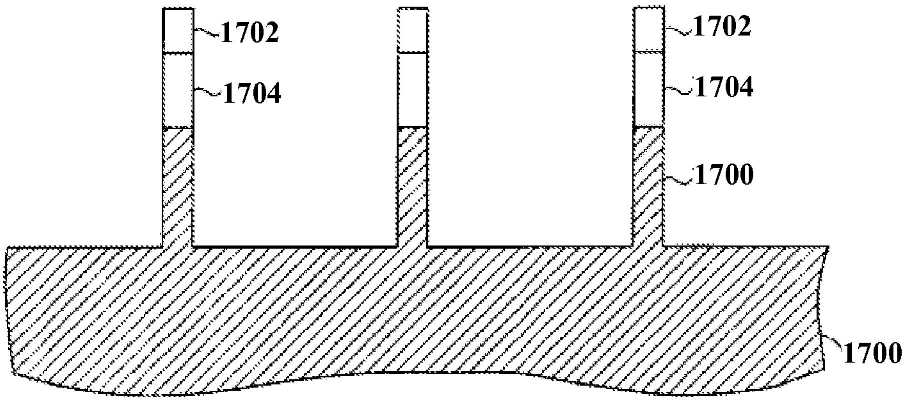


FIG. 17B

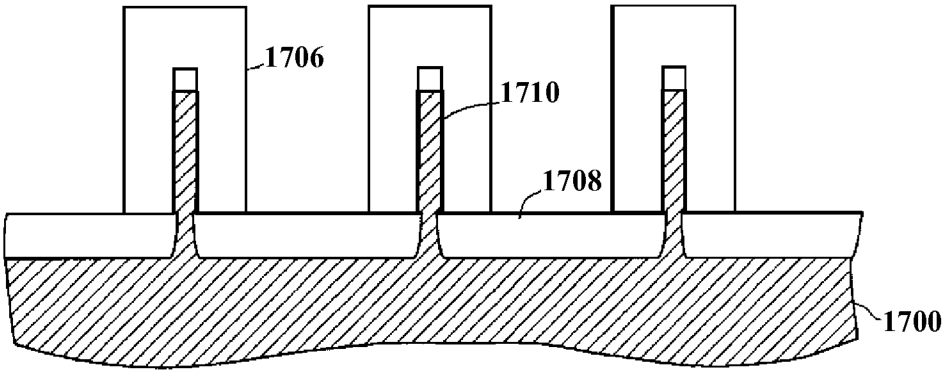


FIG. 17C

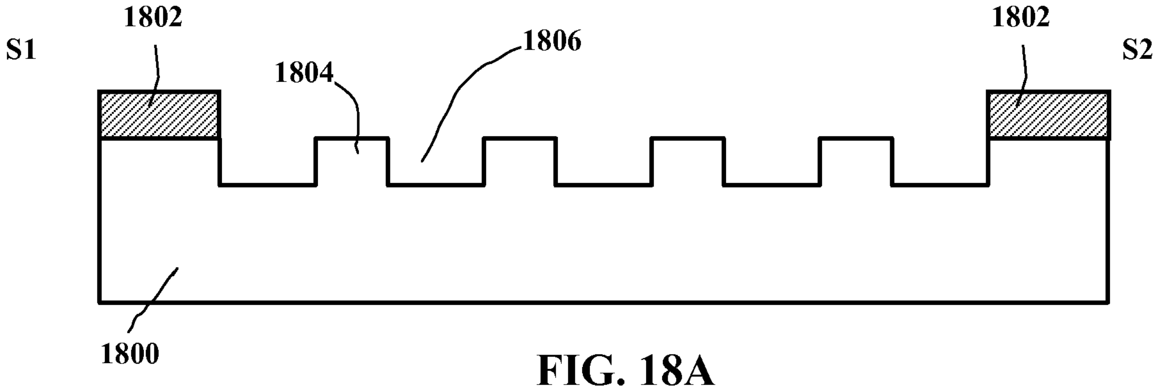


FIG. 18A

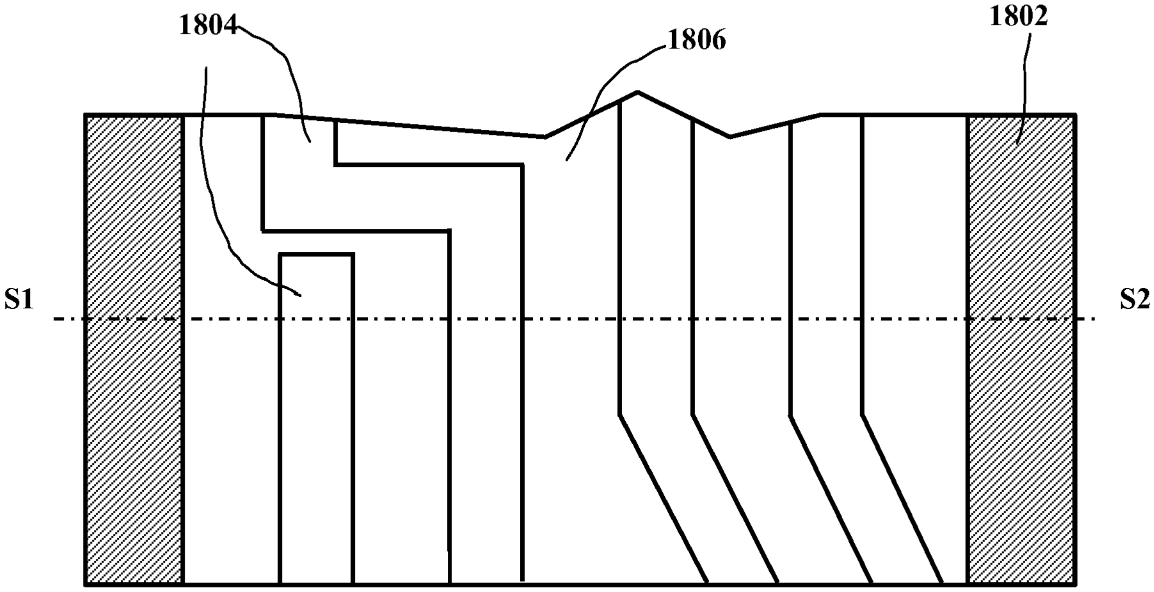


FIG. 18B

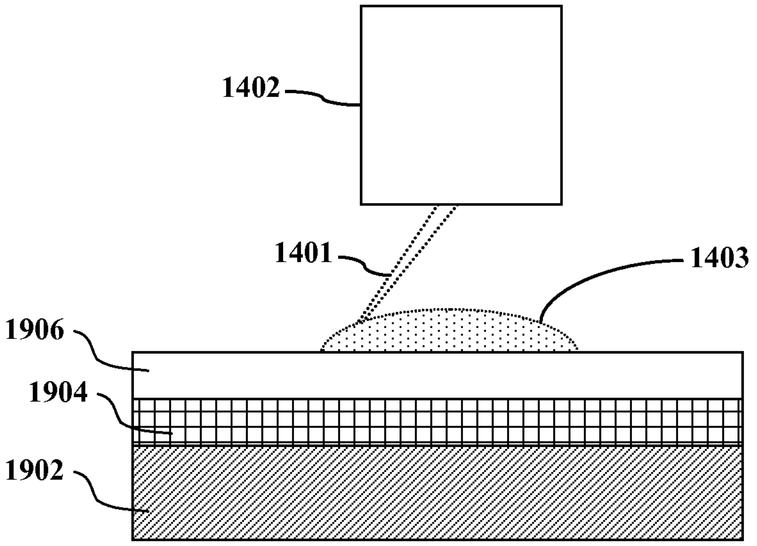


FIG. 19A

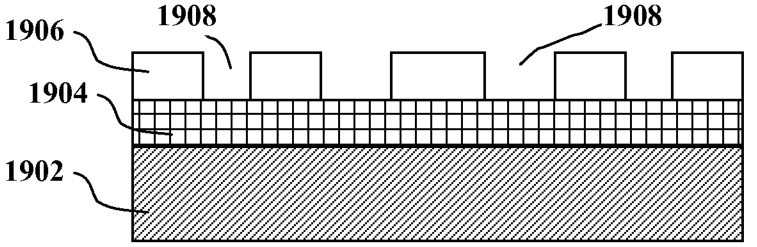


FIG. 19B

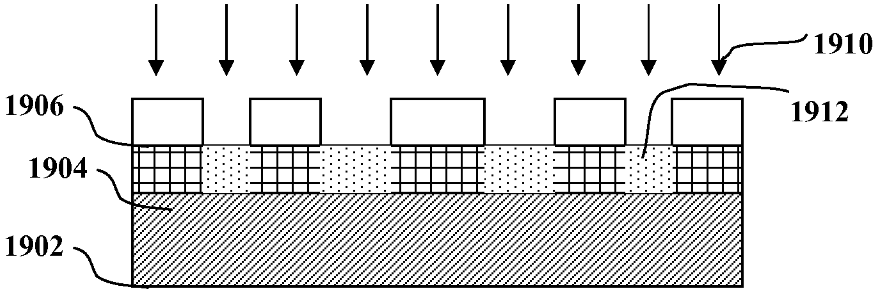


FIG. 19C

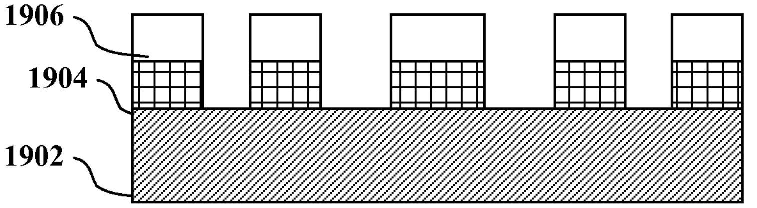


FIG. 19D

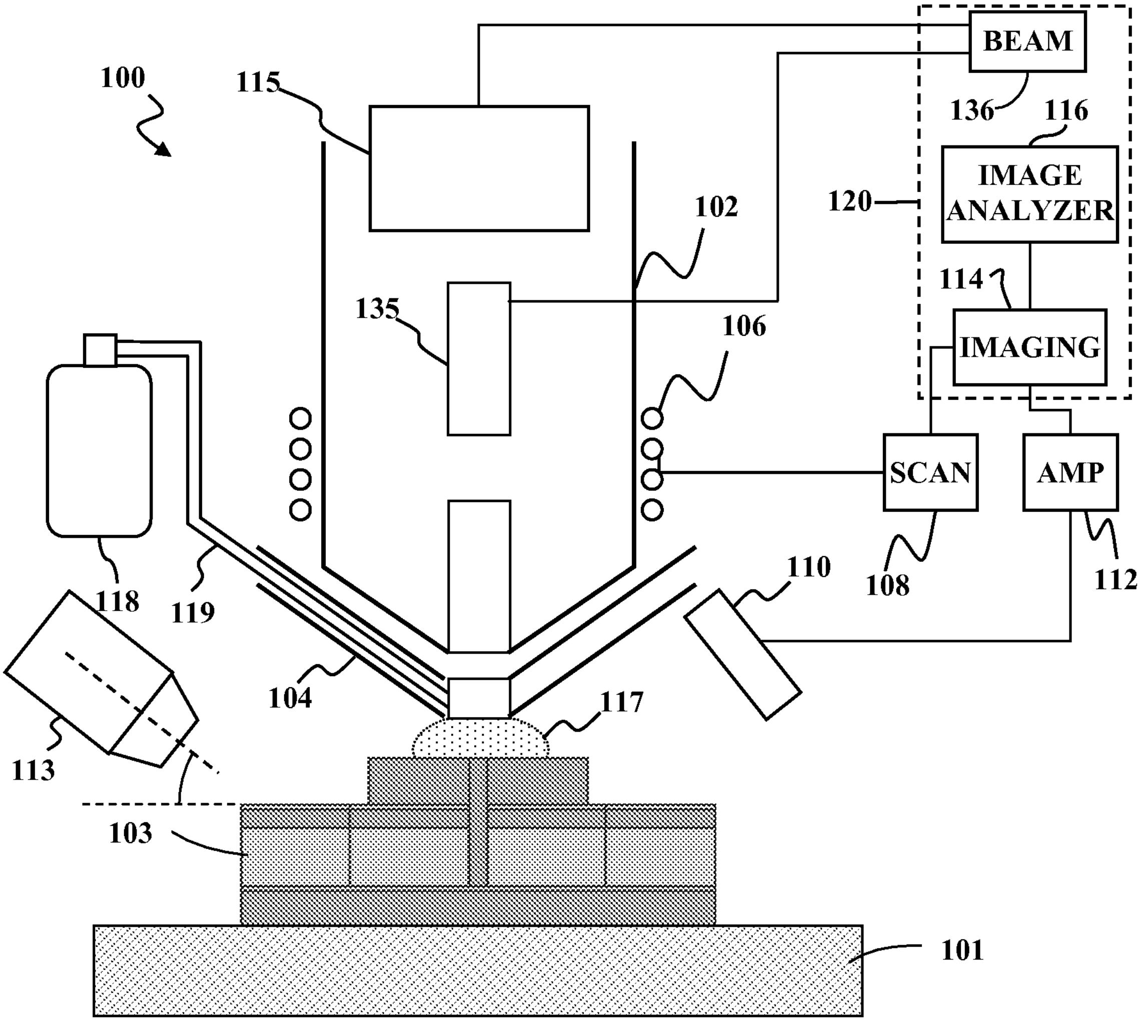

BEAM
136
116
IMAGE ANALYZER
120
114
IMAGING
SCAN
AMP
108
112
100
115
102
135
106
118
119
110
104
117
113
103
101

FIG. 20

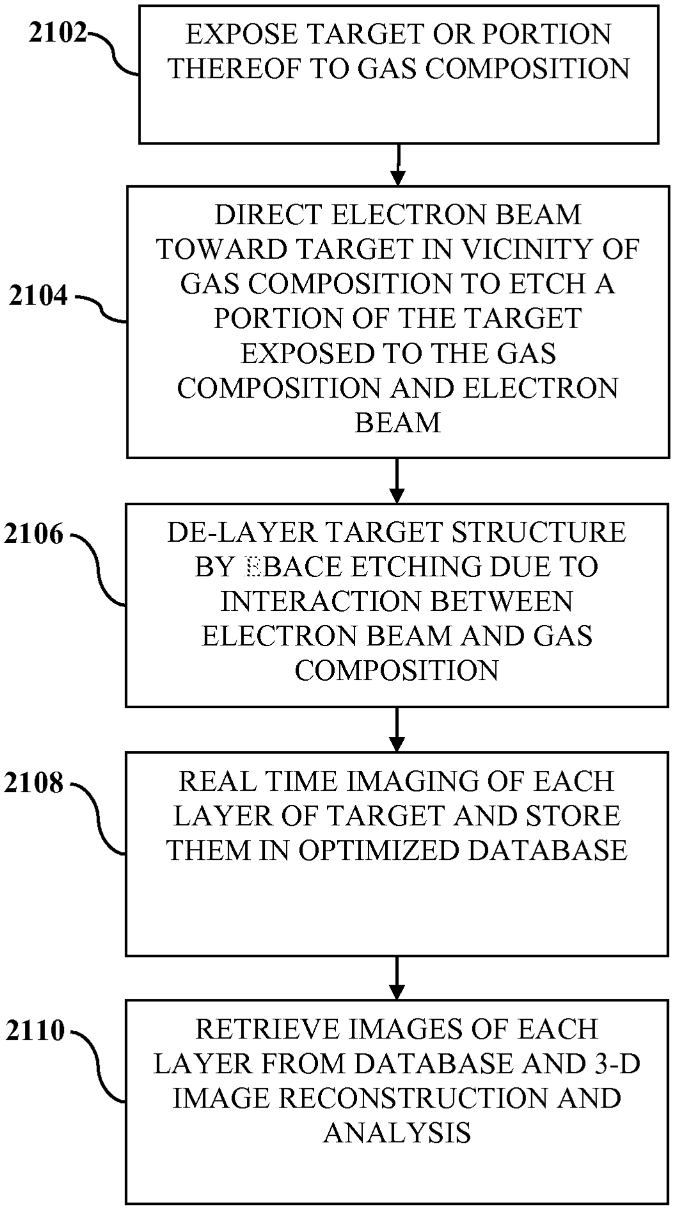

2102
EXPOSE TARGET OR PORTION THEREOF TO GAS COMPOSITION
2104
DIRECT ELECTRON BEAM TOWARD TARGET IN VICINITY OF GAS COMPOSITION TO ETCH A PORTION OF THE TARGET EXPOSED TO THE GAS COMPOSITION AND ELECTRON BEAM
2106
DE-LAYER TARGET STRUCTURE BY EBACE ETCHING DUE TO INTERACTION BETWEEN ELECTRON BEAM AND GAS COMPOSITION
2108
REAL TIME IMAGING OF EACH LAYER OF TARGET AND STORE THEM IN OPTIMIZED DATABASE
2110
RETRIEVE IMAGES OF EACH LAYER FROM DATABASE AND 3-D IMAGE RECONSTRUCTION AND ANALYSIS

FIG. 21

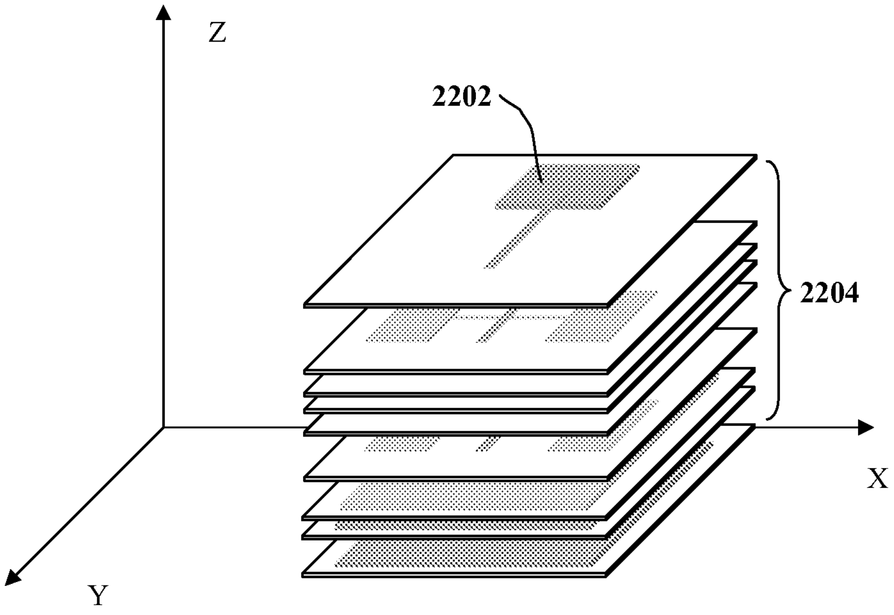


FIG. 22A

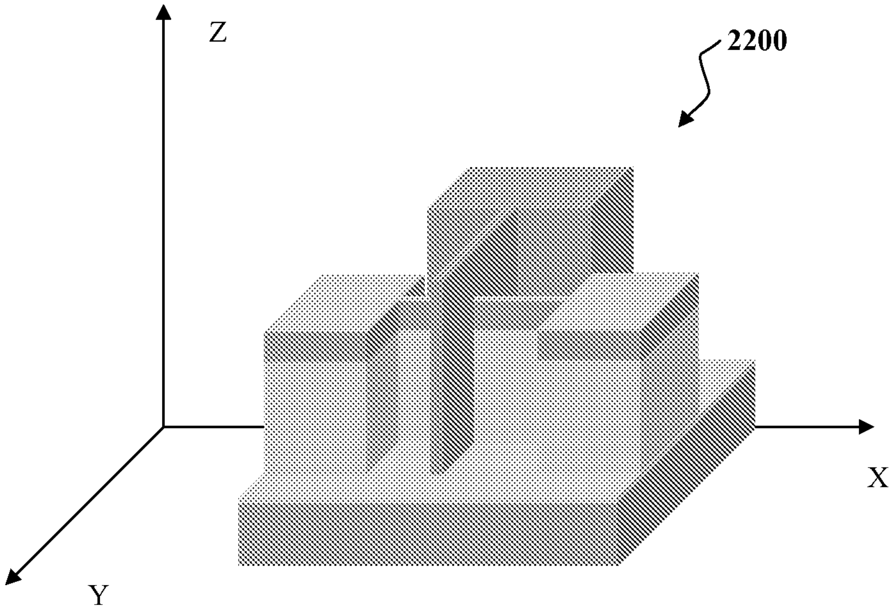


FIG. 22B