



(51) International Patent Classification:

G03F 7/20 (2006.01) *H01J 37/317* (2006.01)
G01N 23/225 (2018.01) *H01L 21/67* (2006.01)
H01J 37/08 (2006.01) *G03F 1/72* (2012.01)
H01J 37/20 (2006.01) *G03F 1/74* (2012.01)
H01J 37/28 (2006.01)

(21) International Application Number:

PCT/EP2019/077927

(22) International Filing Date:

15 October 2019 (15.10.2019)

(25) Filing Language:

English

(26) Publication Language:

English

(30) Priority Data:

62/746,191 16 October 2018 (16.10.2018) US

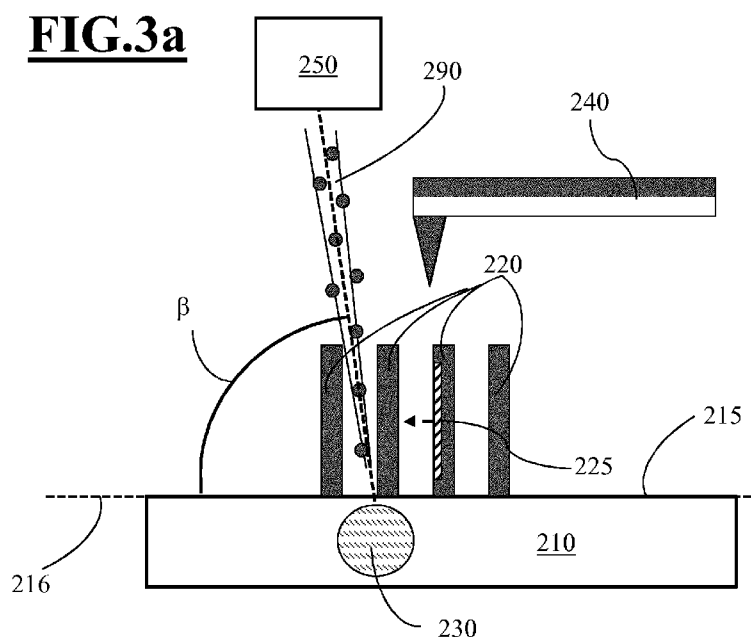
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(81) Designated States (*unless otherwise indicated, for every kind of national protection available*): AE, AG, AL, AM, AO, AT, AU, AZ, BA, BB, BG, BH, BN, BR, BW, BY, BZ, CA, CH, CL, CN, CO, CR, CU, CZ, DE, DJ, DK, DM, DO, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, GT, HN,

(54) Title: METHOD FOR MOVING A STRUCTURE ON A SEMICONDUCTOR ARTICLE AND INSPECTION DEVICE FOR INSPECTING A SEMICONDUCTOR ARTICLE



(57) Abstract: The invention describes a method for moving a structure (220) on a semiconductor article (180, 410) comprising providing a focused charged particle beam device (250), providing a semiconductor article (180, 410) comprising a substrate (210), a surface and a structure (220). The method continues with then defining a region of interest (225) on the structure (220) and defining a modification region (230) in the substrate (210), where the modification region (230) is different from the region of interest (225) and finally modifying the substrate (210) with the focused charged particle beam device (250) in the modification region (230) to move the structure (220). In addition, the invention describes an inspection device for inspecting a semiconductor article (180, 410) with a method as outlined above comprising - A focused charged particle beam device (250) - A semiconductor article holder on a semiconductor

HR, HU, ID, IL, IN, IR, IS, JO, JP, KE, KG, KH, KN, KP, KR, KW, KZ, LA, LC, LK, LR, LS, LU, LY, MA, MD, ME, MG, MK, MN, MW, MX, MY, MZ, NA, NG, NI, NO, NZ, OM, PA, PE, PG, PH, PL, PT, QA, RO, RS, RU, RW, SA, SC, SD, SE, SG, SK, SL, SM, ST, SV, SY, TH, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VC, VN, ZA, ZM, ZW.

(84) Designated States (*unless otherwise indicated, for every kind of regional protection available*): ARIPO (BW, GH, GM, KE, LR, LS, MW, MZ, NA, RW, SD, SL, ST, SZ, TZ, UG, ZM, ZW), Eurasian (AM, AZ, BY, KG, KZ, RU, TJ, TM), European (AL, AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, HR, HU, IE, IS, IT, LT, LU, LV, MC, MK, MT, NL, NO, PL, PT, RO, RS, SE, SI, SK, SM, TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, KM, ML, MR, NE, SN, TD, TG).

Published:

— *with international search report (Art. 21(3))*

METHOD FOR MOVING A STRUCTURE ON A SEMICONDUCTOR ARTICLE
AND INSPECTION DEVICE FOR INSPECTING A SEMICONDUCTOR ARTICLE

As miniaturization of integrated circuits continues, photolithography processes that use deep ultraviolet (DUV) radiation are often inadequate, typically at the wavelength of 193 nm. In order to support the further miniaturization, radiation with a wavelength that is an order of magnitude shorter than that of DUV radiation is required. Developers of photolithography processes have turned to extreme ultraviolet (EUV) radiation. For example, EUV photolithography may utilize radiation at the wavelength 13.5 nm. A typical 13.5 nm radiation source includes a plasma (e.g., a laser-produced plasma) in which the radiation is produced.

Photolithographic masks must be largely error-free, since an error in the mask would reproduce on every wafer with every exposure. In a photolithographic mask, it is important that the pattern elements of the absorber structure on the photolithographic mask exactly map the structural elements specified by the design of the semiconductor device into the photoresist on the wafer. The nominal size of the structural elements generated by the absorber pattern in the photoresist is called critical dimension (CD). This size and its variation (CDU Critical Dimension Uniformity) are some of the central parameters for the quality of a photolithographic mask.

The patterns on the mask are transferred onto the wafer via a lithography lens system which in the working wavelength of EUV radiation range is a purely catoptric system. On the wafer a photosensitive resist is then exposed to the image of the mask. The final exposed wafers contain many microchips that also need to be completely error-free to guarantee the proper functioning of the microchip. The electronic structures on the chips comprise several building blocks. They range from isolated lines over dense and semi-dense lines and spaces, contact holes to full transistor structures like MOSFET or the particular FinFET structure.

With the packing density of the structures rising their respective sizes (CD) and their distances decrease. Furthermore the complexity of the structures in their vertical stacking size increases as well leading to many layers on top of each other. This leads to structures

with a cross section that shows ever increasing aspect ratios, where an aspect ratio can be defined as the ratio of the width of a structure (e.g. the CD) to the height of the structure.

If at some stage in the lithography process an error in one of the structures is detected it is important to analyze this faulty structure in detail to find ways to improve the production process. Additionally as structure sizes decrease random variations in the width of structures are of increasing importance. These random variations can be seen e.g. as varying thicknesses and roughnesses in the sidewalls of structures. This is called line edge roughness (LER) if talking about just one side of a structure or line width roughness (LWR) if talking about the width of a structure.

- 10 The combination of an increasing packing density and increasing aspect ratio make it necessary to obtain information of the full surface and not only the line edges. For high aspect ratio structures it is often not enough to measure the roughness only at the top or at a certain cross section, as the roughness varies from top to bottom and with the lateral position. However, the sidewalls of the structures are often not accessible for measuring devices which can acquire areal surface information.

- Typically vertical bar structures are separated by 20 nm or even less but having heights of e.g. 100 nm. There exists currently no method for obtaining quantitative areal roughness information for the vertical sidewalls. Currently, the only way to measure the roughness is by SEM imaging from the top, SEM imaging of a cross section made by a focused ion beam, by making a TEM preparation. The first method can differentiate between selected structures but yields only information from the top of the structure. TEM preparation has the disadvantage that it is very time consuming and positioning the slice is not precise. Both SEM and TEM imaging deliver only one dimensional LER and LWR values. Features like spikes to the side which only occur seldom are likely to be missed by both methods. None of the methods so far allows selecting a certain structure to be investigated and then fully exposing this surface to perform a full two dimensional surface analysis.

- Another method one could think of is cutting the neighbor fins away with a beam of focused ions. The problem here is that because of material re-deposition the surface to be investigated is contaminated. A protective coating to cover the structures of interest could

be applied before performing the FIB cutting and selectively etching the coating after cutting. This protective coating, however, will not go into the small gaps of 10 nm and below. Furthermore the FIB cutting to stop at the right structure with nm precision without damaging the surface can not be controlled well enough.

- 5 It is therefore an object of the present invention to provide a method to make previously inaccessible parts of structures of semiconductor articles accessible to measurement devices without contaminating the measurement result.

This object is solved by moving a structure on a semiconductor article comprising the steps:

- 10
- Providing a focused charged particle beam device
 - Providing a semiconductor article comprising a substrate, a surface and a structure
 - Defining a region of interest on the structure
 - Defining a modification region in the substrate, where the modification region is different from the region of interest
- 15
- Modifying the substrate with the focused charged particle beam device in the modification region to move the structure.

A semiconductor article within is understood to be either a mask used for optical lithography, a nanoimprint mask, an exposed wafer, either after all exposures are finished or at an intermediate step, as well as parts of these elements.

- 20 The semiconductor article comprises a substrate. This substrate has a surface and on this surface some structures are disposed. In the case of a lithography mask the substrate can be a glass substrate and the structures could be chrome features that are meant to be imaged onto the wafer. In the case of a wafer the substrate might be the semiconductor e.g. crystalline silicon, germanium, gallium nitride, gallium arsenide, silicon germanium
- 25 or any other semiconductor material. The surface of the semiconductor article is to be understood as the actual surface of the material including any roughness and variation. It should be distinguished from the reference surface plane. This reference surface plane is thought to be an ideal plane that can describe the surface in mathematical terms. This could be the best fit plane to a region of the actual surface of the semiconductor article. While

in most circumstances a plane will be used as the reference surface, it is also possible to use a curved surface as a reference surface e.g. to take any stresses or mounting effects into account.

Typically, the structures are disposed on top of the substrate. Many identical structures
5 can be arranged next to each other. On one or more of these structures a region of interest (ROI) is defined. This region of interest may be a part of the sidewall of a line, the whole side of a fin of a FinFET or some other region.

The inventors have realized that it is possible to move this region of interest with the use of a focused charged particle beam without contaminating the ROI. Several devices are
10 available for generating focused charged particle. In particular, this can be an electron beam as generated by electron microscopes or it could be a focused ion beam (FIB).

In effect this beam is used as a nano manipulator device. Other such devices that use a different working mechanism to move the structure on the substrate of the semiconductor article can also be devised.

15 In a next step of the method a modification region in the substrate is defined. This serves as a target for the focused charged particle beam. It is important that the region of interest and the modification region are different from each other. This has the advantage that a contamination of the ROI can be avoided. Thus by directing the focused charged particle device onto the modification region within the substrate of the semiconductor article, the
20 structure with the region of interest is moved. It is advantageous, if the modification region is far enough away from the ROI so not to contaminate that region while still being close enough to effect a motion of the structure. The particular distances will depend on the material of the substrate, the size of the structure and other parameters.

In another aspect of the invention a gas field ion microscope is used as a focused charged
25 particle device.

In another aspect of the invention the gas used to form the gas ions comprises a noble gas i.e. one of one of Helium, Neon, Argon, Krypton or Xenon.

In another aspect of the invention one of an electron gun or a metal ion gun is used as the focused charged particle device. These types of focused charged particle device are commonly known. An electron gun is described in

https://en.wikipedia.org/wiki/Transmission_electron_microscopy#/media/File:Electron-gun.svg and a metal ion gun in EP 0 091 777 A2.

The gas ions are directed towards the modification region in the substrate. In the substrate the ions combine with surrounding electrons to form electrically neutral gas atoms. These gas atoms accumulate within the modification region in the substrate. The modification region does not have clear boundary. It serves as a target area for the gas ions. The gas ions then form one or more gas bubbles within the substrate. These gas bubbles are centered around the modification region

In another aspect of the invention a measuring device to measure a property of the structure is provided. With this measuring device the region of interest can be investigated. A wide variety of measuring devices is known. Measuring devices can comprise an optical microscope, an electron microscope, a mass spectrometer, a scanning probe microscope (SPM). It is also possible to combine several measuring devices in parallel or sequentially. Roughness values in the ROI of the structure are typically of a scale below 1 nm, current noise levels of sidewalls are around 100 picometer. Therefore, a measuring device that can support a resolution that can resolve these features is preferred. Current SPM system can achieve a noise level in the range of 20 picometer. Therefore, the use of an SPM is especially advantageous.

Scanning probe microscopes scan a sample or the surface thereof with a probe and thereby provide measurement data for producing a representation of the topography of the sample surface. A distinction is made between various SPM types, depending on the type of interaction between the measurement tip of a probe and the sample surface.

Frequently, scanning tunneling microscopes (STM) are used in which a voltage is applied between the sample and the measurement tip, which are not in contact with one another, and the resulting tunnel current is measured.

In the case of the scanning force microscope (SFM, or AFM for atomic force microscope), the measurement tip is deflected by way of atomic forces of the sample

surface. The force/distance relation is typically described by the Lennard-Jones potential. The deflection of the measurement tip is roughly proportional to the force acting between measurement tip and the sample surface. By keeping this force constant during scanning, the surface topography can be recorded.

- 5 In addition to these common SPM types, there are a multiplicity of further device types and operation modes which are used for specific fields of application, such as magnetic force microscopes or near-field scanning optical and acoustic microscopes.

Typical SPM types may have difficulty analyzing structures on a sample which have a high aspect ratio, i.e. a high quotient of depth or height of a structure to its smallest lateral
10 extent. For this reason, standard SPMs can image deep trenches and steep flanks to only a limited extent. The limiting effect here is the finite radius of the measurement tip of SPM probes, in particular the cone angle thereof.

In another aspect of the invention the method comprises moving the structure, where the structure comprises at least one side not accessible to the measuring device and a region
15 of interest that is at least partially located on this side, to a position, where the region of interest is accessible to the measuring device and subsequently measuring a property of the structure in at least a part of the region of interest.

A variety of properties can be measured. Of particular importance are the line edge roughness (LER) and the line width roughness (LWR) and areal surface roughness
20 parameters. These areal surface parameters are becoming increasingly important. The ISO 25178 norm defines several parameters. Areal surface parameters are able to describe the topography of a surface in more detail than the single number parameters LER and LWR. It can also be envisioned to parametrize a surface in an areal base expansion. The actual base functions will depend on the shape of the surface. Well
25 known examples for one-dimensional functions are Legendre-polynomials, Hermite polynomials or others. These can be easily generalized to the 2-D case of surfaces. An example for functional basis on the unit circle are e.g. the Zernike polynomials. Furthermore other properties like conductivity, work function or to some extent viscosity can be measured.

In another aspect of the invention the inventors realized that to expose the region of interest on the structure to the measuring tip of an AFM or SPM the structure should be tilted by an angle β . Since the sidewall should be accessible to the measuring tip it should at least be tilted by an angle of 45° , preferably by an angle of 60° more preferably by an angle of 90° .

Alternatively, the feature to be investigated could be just vertically lifted. In this case a special sidewall scanning procedure e.g. with a sphere AFM tip would be preferred. Due to the nature of the deposition process combinations of lifting and tilting of the structure are also possible.

10 In another aspect of the invention the substrate of the semiconductor article comprises a crystalline material. Typical crystalline materials comprise one of silicon, germanium, diamond, SiSiC, GaN, SiGe, GaAs. Without being bound by theory it is thought that the gas atoms accumulate and grow to build bubbles filled with gas in the crystal lattice. These gas bubbles are located in the modification region of the substrate. While the method is used to move structures on semiconductor articles, the deposition of gas bubbles in a crystalline material could conceptually also be used in other areas e.g. in mineralogy.

20 In another aspect of the invention the deposition of the particles of the focused charged particle beam device in the modification region of the substrate thereby causes a change in volume of the at least the modification region. This change in volume in the modification region leads to mechanical stresses in the substrate. The material of the substrate then reacts to these stresses by deforming. In particular a change in the surface of the substrate can occur. This in turn leads to moving the structure with the ROI on the surface of the substrate of the semiconductor article.

25 In some instances, it is sufficient to move the structure with the ROI on the surface to be accessible to the measuring device. Therefore a permanent change in the volume of at least the modification region would be acceptable. In other cases, the change in volume of at least the modification region can be reversible. Thus the gas bubbles could be removed e.g. by diffusion processes from the substrate of the semiconductor article.

Therefore, there is one aspect of the invention, where the change in volume of at least the modification region of the substrate is an increase in volume. This increase in volume leads to a bulging or swelling in the substrate when compared with the reference surface plane of the substrate.

In another aspect of the invention the change in volume of at least the modification region of the substrate is a decrease in volume. In particular, when using a focused electron device a compaction of the substrate in the modification region can be effected. This compaction leading to a depression in the substrate when compared with the reference surface plane of the substrate. Causing a depression in at least the modification region of the substrate will cause the structures near the modification region to tilt inwards towards the modification region. In the case of an increase of the volume in at least the modification region of the substrate will cause the structures near the modification region to tilt away from the modification region.

The inventors realized that it is important to control the movement of the structures in particular of the structure with the ROI that is inaccessible to the measuring device. Several parameters can be used to control the motion of the ROI on the structure on top of the substrate.

In one aspect of the invention the beam of charged particles forms an angle α between the direction of charged particle and the reference surface plane of the substrate. Controlling this angle allows different positions of the modification region. Since the charged particles penetrate a certain distance into the material, changing the angle α allows the positioning of the modification region under the structure with the ROI. Another parameter to control the change in volume and therefore in turn the motion of the structure with the ROI is to change the penetration depth of the charged particle. This can be done by changing the average energy of the charged particles. Often this is controlled by the acceleration voltage of the focused charged particle device.

In another aspect of the invention a dwell time of the focused charged particle beam in the modification region is controlled. The longer the dwell time in a particular

modification region is the more charged particles can accumulate in the modification region. Therefore, for an electron beam the compaction increases with longer dwell time. This in turn leads to a larger tilt of the structure with the ROI. In the case of a deposition of gas bubbles a longer dwell time leads to a larger amount of deposited gas. This in turn
5 leads to larger gas bubbles and a larger change in volume of at least the modification region of the substrate. This will create a larger tilt of the structure with the ROI.

In another aspect of the invention the motion of the structure with the ROI is controlled by setting a spot size of the focused charged particle beam on the surface of the semiconductor article. By setting the spot size a larger or smaller modification region can
10 be affected. In this way the modification region forms a voxel within the substrate of the semiconductor article. The size of this voxel corresponds to the size of the spot of the focused charged particle beam. In another aspect of the invention more than one of these voxels can be arranged in the substrate of the semiconductor device. This is the same as defining several modification regions in the substrate. These modification regions or
15 voxels can then be arranged in pattern to affect a more complex motion of the structure with the ROI or to affect more than one structure with more than one region of interest. Alternatively, these voxels can be combined to form elongated or curved modification regions.

In another aspect of the invention the semiconductor article is cut to guide the motion of
20 the structure. The technique of relation cuts is well known from classical mechanics. Trenches can be cut into the surface of the substrate of the semiconductor article. These can be used to guide the motion induced by the volume change of the modification region. Depending on the direction, these cuts can be used to enhance or lessen the motion. If a focused gas ion beam device is used as a focused charged particle device,
25 this can also be used to create the cuts. In another aspect one kind of gas, e.g. helium ions, is used to deposit gas in the substrate and a second kind of gas, e.g. neon ions, is used to create the guiding cuts in the substrate.

In another aspect of the invention the focused charged particle beam device is used to record an image of the semiconductor article, while modifying the substrate. This has the
30 advantage that during the deposition of the charged particles within the modification

region of the substrate the correct positioning of the charged particle beam can be controlled, thus ascertaining that the ROI on the structure that is to be tilted is not contaminated or otherwise directly affected.

In another aspect of the invention the inventors realized that an iteration between a deposition of material and a removal of substrate may be necessary. The focused charged particle beam is then used to remove at least part of the increased volume of the substrate. Typically, the deposition of any gas bubbles will occur within a penetration depth. Therefore, the gas bubbles will be located some distance in the substrate. This distance may be 100 nm or more. The material that will be removed, will be removed from the deformed surface of the substrate. Therefore, it will be material of the original substrate of the semiconductor article.

In another aspect of the invention the particles used for the volume removal are different from the particles used for the increase in volume of the modification region.

In another aspect of the invention multiple steps of increasing the volume of the modification region and/or removing parts of increased volume are sequentially executed.

The above methods can be executed with an inspection device for inspecting a semiconductor article. This inspection device needs a focused charged particle beam device, a semiconductor article holder on a semiconductor article stage, a measuring device and an electronic control system for the charged particle beam device.

As a measuring device a scanning probe microscope in particular an atomic force microscope is preferable.

If more than one modification region or voxel needs to be modified within the substrate of the semiconductor article, the focused charged particle beam needs to scan over the surface of the semiconductor article. To achieve this the inspection comprises a scanning device for scanning the charged particle beam device.

To achieve additional positioning capabilities a sample stage and a sample holder that can be moved laterally and/or vertically. Additionally tilting capability of the sample stage and the sample holder are also preferable. Since in the context of the present invention

the sample is always a semiconductor article, the terms semiconductor article and sample are synonymous.

In another aspect the inspection device comprises an imaging unit connected to the focused charged particle beam device for generation of images of the surface of the substrate and/or a measurement collection unit connected to the measuring device.

BRIEF DESCRIPTION OF THE DRAWINGS

Fig. 1 schematically illustrates a gas focused ion beam system.

Fig. 2 schematically illustrates the creation of gas ions in a gas focused ion beam system.

Fig. 3a schematically illustrates the method of the invention at a time of starting the method. The ROI is not accessible to the measuring device.

Fig. 3b schematically illustrates the method of the invention at a time when the region of interest on the structure has been moved and the region of interest has been made accessible to the measuring device.

Fig. 4 schematically illustrates an atomic force microscope.

List of reference numbers

	100	Gas field ion microscope
20	110	Gas source
	120	Gas field ion source
	130	Ion optics
	140	Sample manipulator
	150	Front side detector
25	160	Back side detector
	170	Electronic control system
	172a-172f	Communication lines

	180, 410	Sample, semiconductor article
	181, 215, 415	Surface of sample, surface of semiconductor article
	182	Gas
	186	Electrically conductive tip of gas field ion microscope
5	187	Tip apex of gas field ion microscope
	188	Suppressor
	190	Extractor
	192	Ion beam
	194	Particles
10	210	Substrate of semiconductor article
	216	Reference surface plane
	220	Structure of semiconductor article
	225	Region of interest
	230	Modification region
15	240	Measuring device
	250	Focused charge particle device
	290	Charged particle beam
	400	Atomic force microscope
	420	Scanning device of AFM
20	425	Sample stage, semiconductor article stage
	430	Measurement tip of AFM
	440	Cantilever of AFM
	450	Attachment unit
	455	Probe
25	460	Laser system
	465	Laser beam
	470	Photodetector
	480	Control device of AFM
	482	Second connection of AFM
30	484	Supply line of AFM
	490	Second laser system

495

Laser beam

Description of drawings

5

Ions can be produced and used for sample imaging and other applications in microscope systems. Microscope systems that use a gas field ion source to generate ions that can be used in sample analysis (e.g., imaging) are referred to as gas field ion microscopes. A gas field ion source is a device that includes an electrically conductive tip (typically

10 having an apex with 10 or fewer atoms) that can be used to ionize neutral gas species to generate ions (e.g., in the form of an ion beam) by bringing the neutral gas species into the vicinity of the electrically conductive tip (e.g., within a distance of about four to five angstroms) while applying a high positive potential (e.g., one kV or more relative to the extractor (see discussion below)) to the apex of the electrically conductive tip.

15 FIG. 1 shows a schematic diagram of a gas field ion microscope system 100 that includes a gas source 110, a gas field ion source 120, ion optics 130, a sample manipulator 140, a front-side detector 150, a back-side detector 160, and an electronic control system 170 (e.g., an electronic processor, such as a computer) electrically connected to various components of system 100 via communication lines 172a-172f. A

20 sample 180 is positioned in/on sample manipulator 140 between ion optics 130 and detectors 150, 160. During use, an ion beam 192 is directed through ion optics 130 to a surface 181 of sample 180, and particles 194 resulting from the interaction of ion beam 192 with sample 180 are measured by detectors 150 and/or 160.

25 In general, it is desirable to reduce the presence of certain undesirable chemical species in system 100 by evacuating the system. Typically, different components of system 100 are maintained at different background pressures. For example, gas field ion source 120 can be maintained at a pressure of approximately 10^{-10} Torr. When gas is introduced into gas field ion source 120, the background pressure rises to approximately 10^{-5} Torr. Ion optics

30 130 are maintained at a background pressure of approximately 10^{-8} Torr prior to the

introduction of gas into gas field ion source 120. When gas is introduced, the background pressure in ion optics 130 typically increase to approximately 10^{-7} Torr.

Sample 180 is positioned within a chamber that is typically maintained at a background
5 pressure of approximately 10^{-6} Torr. This pressure does not vary significantly due to the presence or absence of gas in gas field ion source 120.

As shown in FIG. 2, gas source 110 is configured to supply one or more gases 182 to gas field ion source 120. As described in more detail below, gas source 110 can be
10 configured to supply the gas(es) at a variety of purities, flow rates, pressures, and temperatures. In general, at least one of the gases supplied by gas source 110 is a noble gas (helium (He), neon (Ne), argon (Ar), krypton (Kr), xenon (Xe)), and ions of the noble gas are desirably the primary constituent in ion beam 192. In general, as measured at surface 181 of sample 180, the current of ions in ion beam 192 increases monotonically
15 as the pressure of the noble gas in system 100 increases. In certain embodiments, this relationship can be described by a power law where, for a certain range of noble gas pressures, the current increases generally in proportion to gas pressure. During operation, the pressure of the noble gas is typically 10^{-2} Torr or less (e.g., 10^{-3} Torr or less, 10^{-4} Torr or less), and/or 10^{-7} Torr or more (e.g., 10^{-6} Torr or more, 10^{-5} Torr or more) adjacent the
20 tip apex (see discussion below). In general, it is desirable to use relatively high purity gases (e.g., to reduce the presence of undesirable chemical species in the system). As an example, when He is used, the He can be at least 99.99% pure (e.g., 99.995% pure, 99.999% pure, 99.9995% pure, 99.9999% pure). Similarly, when other noble gases are used (Ne gas, Ar gas, Kr gas, Xe gas), the purity of the gases is desirably high purity
25 commercial grade.

Optionally, gas source 110 can supply one or more gases in addition to the noble gas(es). As discussed in more detail below, an example of such a gas is nitrogen. Typically, while the additional gas(es) can be present at levels above the level of impurities in the noble
30 gas(es), the additional gas(es) still constitute minority components of the overall gas mixture introduced by gas source 110. As an example, in embodiments in which He gas

and Ne gas are introduced by gas source 110 into gas field ion source 120, the overall gas mixture can include 20% or less (e.g., 15% or less, 12% or less) Ne, and/or 1 % or more (e.g., 3% or more, 8% or more) Ne. For example, in embodiments in which He gas and Ne gas are introduced by gas source 110, the overall gas mixture can include from 5% to 5 15% (e.g., from 8% to 12%, from 9% to 11 %) Ne. As another example, in embodiments in which He gas and nitrogen gas are introduced by gas source 110, the overall gas mixture can include 1 % or less (e.g., 0.5% or less, 0.1 % or less) nitrogen, and/or 0.01 % or more (e.g., 0.05% or more) nitrogen. For example, in embodiments in which He gas and nitrogen gas are introduced by gas source 110, the overall gas mixture can include 10 from 0.01 % to 1 % (e.g., from 0.05% to 0.5%, from 0.08 to 0.12%) nitrogen. In some embodiments, the additional gas(es) are mixed with the noble gas(es) before entering system 100 (e.g., via the use of a gas manifold that mixes the gases and then delivers the mixture into system 100 through a single inlet). In certain embodiments, the additional gas(es) are not mixed with the noble gas(es) before entering system 100 (e.g., a separate 15 inlet is used for inputting each gas into system 100, but the separate inlets are sufficiently close that the gases become mixed before interacting with any of the elements in gas field ion source 120).

Gas field ion source 120 is configured to receive the one or more gases 182 from gas 20 source 110 and to produce gas ions from gas(es) 182. Gas field ion source 120 includes an electrically conductive tip 186 with a tip apex 187, an extractor 190 and optionally a suppressor 188. Typically, the distance from tip apex 187 to surface 181 of sample 180 (not shown in FIG. 2) is five cm or more (e.g., 10 cm or more, 15 cm or more, 20 cm or more, 25 cm or more), and/or 100 cm or less (e.g., 80 cm or less, 60 cm or less, 50 cm or 25 less). For example, in some embodiments, the distance from tip apex 187 to surface 181 of sample 180 is from five cm to 100 cm (e.g., from 25 cm to 75 cm, from 40 cm to 60 cm, from 45 cm to 55 cm).

Electrically conductive tip 186 can be formed of various materials. In some 30 embodiments, tip 186 is formed of a metal (e.g. tungsten (W), tantalum (Ta), iridium (Ir), rhenium (Rh), niobium (Nb), platinum (Pt), molybdenum (Mo)). In certain

embodiments, electrically conductive tip 186 can be formed of an alloy. In some embodiments, electrically conductive tip 186 can be formed of a different material (e.g., carbon (C)).

5 During use, tip 186 is biased positively (e.g., approximately 20 kV) with respect to extractor 190, extractor 190 is negatively or positively biased (e.g., from -20 kV to +50 kV) with respect to an external ground, and optional suppressor 188 is biased positively or negatively (e.g., from -5 kV to +5 kV) with respect to tip 186. Because tip 186 is formed of an electrically conductive material, the electric field of tip 186 at tip apex 187
10 points outward from the surface of tip apex 187. Due to the shape of tip 186, the electric field is strongest in the vicinity of tip apex 187. The strength of the electric field of tip 186 can be adjusted, for example, by changing the positive voltage applied to tip 186. With this configuration, un-ionized gas atoms 182 supplied by gas source 110 are ionized and become positively-charged ions in the vicinity of tip apex 187. The positively-
15 charged ions are simultaneously repelled by positively charged tip 186 and attracted by negatively charged extractor 190 such that the positively-charged ions are directed from tip 186 into ion optics 130 as ion beam 192. Suppressor 188 assists in controlling the overall electric field between tip 186 and extractor 190 and, therefore, the trajectories of the positively charged ions from tip 186 to ion optics 130. In general, the overall electric
20 field between tip 186 and extractor 190 can be adjusted to control the rate at which positively-charged ions are produced at tip apex 187, and the efficiency with which the positively-charged ions are transported from tip 186 to ion optics 130.

As an example, without wishing to be bound by theory, it is believed that He ions can be
25 produced as follows. Gas field ion source 120 is configured so that the electric field of tip 186 in the vicinity of tip apex 187 exceeds the ionization field of the un-ionized He gas atoms 182, and tip 186 is maintained at a relatively low temperature. When the unionized He gas atoms 182 are in close proximity to tip apex 187, the He atoms can be polarized by the electric field of the tip, producing a weakly attractive force between He atoms 182
30 and tip apex 187. As a result, He atoms 182 may contact tip apex 187 and remain bound (e.g., physisorbed) thereto for some time. In the vicinity of tip apex 187, the electric field

is high enough to ionize He atoms 182 adsorbed onto tip apex 187, generating positively charged He ions (e.g., in the form of an ion beam).

Fig 3a and Fig 3b depict two stages of the inventive method. In Fig. 3a the step at the
5 start of the method is shown. A focused charged particle beam device 250 is provided. The semiconductor article comprises a substrate 210 with a substrate surface 215. A reference substrate plane 216 of the semiconductor article 180 is also depicted with a dotted line. This reference substrate plane serves to define a plane without having to take into account minute variations of the actual surface of the semiconductor article 180. As
10 such the reference surface plane 216 can be the best fit to the real surface or a part of the real surface of the semiconductor article 180. On top of the surface of the semiconductor article structures 220 are positioned. The semiconductor article 180 may be a wafer or a mask for lithography. In both cases a plurality of structures is arranged on the semiconductor device. These structures 220 range from isolated lines over dense and
15 semi-dense lines and spaces, contact holes to full transistor structures like MOSFET or the particular FinFET structure. Only four structures 220 are shown in figure 3a. On one of the structures 220 a region of interest (ROI) 225 is defined. This region of interest 225 is not accessible to a measuring device 240. A modification region 230 is defined within the substrate. This modification region 230 is different from the region of interest 225 on
20 the structure 220. The modification region 230 should be located near the structure 220 with the ROI 225. If the modification region 230 is too far away from the structure 220 with the ROI 225, then it will be difficult to change the modification region 230 so much that a movement of the structure 220 with the ROI 225 can be affected. The best distance will depend on a variety of parameters. The person skilled in art will either easily be able
25 to locate a good position or find a good position by simply repeating the experiment several times. In current semiconductor devices a typical distance will be less than one micrometer, preferably less than 100 nm. The substrate 210 in the modification region 230 is then modified with particles from the focused charged particle device 250 by directing a beam 290 of charged particles at the modification region 230. In the figure the
30 charged particles are depicted symbolically as circles. It is clear that a particle beam 290 will have a distribution of particles with a finite cross section. Since the beam of charged

particles 290 is focused this cross section of the beam will vary with distance from the substrate 210. An average beam direction can be defined. This is shown as the dotted line in the charged particle beam 290.

5 In this particular embodiment a gas field ion microscope is used for providing the focused charged particle beam 290. As a gas helium or neon ions are used. Other gases, preferably noble gases as Argon, Krypton or Xenon are also possible. Smaller ions like helium have the advantage to penetrate more easily into the substrate 210 of the semiconductor article 180. Additionally larger ions are more likely to sputter material of
10 the substrate 210 or surrounding structures 220 away, thus introducing a source for contamination.

The method is particularly suited when the substrate comprises a crystalline material. The crystalline material can comprise one of silicon, germanium, gallium nitride, gallium
15 arsenide, silicon germanium, diamond, SiSiC.

Fig 3a further shows a measuring device 240. The measuring device is can be a scanning probe microscope, in particular an atomic force microscope. The ROI 225 on the structure 220 is not accessible to the measuring device. The width of the structures 220 is
20 typically less than 50nm. In particular if the pitch of repeating structures is small, e.g. smaller than three times of the AFM tip apex diameter the ROI 225 is not accessible. This problem increases for higher aspect ratios of the cross section of the structures 220. Aspect ratios defined as the ratio of width to height of a structure 220 can be e.g. 1:1, 1:10 or 1:100 or any ratio in between.

25

To control the movement of the structure 220 with the ROI 225, it is important to control several aspects of the focused charge particle beam 290. To be able to control these an electronic control system needs to be present in the focused charged particle device 250.

30 One of several control parameters is an angle β between a focused charged particle beam 290 and a reference surface plane 216 of the semiconductor article 180. With this angle β

the charged particle beam 290 is aimed towards the modification region 230. This angle β can be adjusted according to the wanted position of the modification region, the height and pitch of the structures 220 surrounding the structure 220 with the ROI 225. A further parameter can be the dwell time of the charged particle beam 290 on the substrate 210.

5 Furthermore a spot size (not shown) of a focused charged particle beam 290 on the surface 215 of the substrate 210 can be set. With a current gas focused ion beam typical spot sizes are of 1 nm diameter or less. The spot size can be changed by changing the focus on the ion optics of the focused charged particle beam device 250.

10 Fig. 3b shows the situation after the method has been performed. The focused charged particle beam device 250 does not emit any charged particles. The particles, in this case the helium ions that have recombined to helium atoms, have been deposited in the modification region 230. The helium atoms are depicted as small white circles. The particles can aggregate in small gas bubbles in and around the modification region 230.

15 They could also integrate into the crystal lattice of the substrate 210. How the particles are arranged within the substrate 210 can vary from substrate material to substrate material. In experiments with a crystalline silica substrate and helium ions several voids or gas bubbles of different sizes were created. The sizes of these bubbles were observed to be less than 20 nm in diameter. Many were less than this diameter. The important

20 feature is that in every case an effect on the substrate 210 is observed. The deformation of the surface 215 of the substrate 210 moves the structure 220 with the ROI 225. In the case of Fig 3b it has been moved so that the ROI 225 is now accessible to the measuring system 240. In a next step a property of the structure 220 in at least a part of the region of interest 225 is measured. A topographical map of the ROI 225 can then be created.

25

Of particular importance are the line edge roughness (LER) and the line width roughness (LWR) and areal surface roughness parameters. These areal surface parameters are becoming increasingly important. The ISO 25178 norm defines several parameters. Areal surface parameters are able to describe the topography of a surface in more detail than the

30 single number parameters LER and LWR. It can also be envisioned to parametrize a surface in a mathematical expansion. The actual base functions will depend on the shape

of the surface. Well known examples for one-dimensional functions are Legendre-polynomials, Hermite polynomials or others. These can be easily generalized to the 2-D case of surfaces. An example for functional basis on the unit circle are e.g. the Zernike polynomials. Furthermore other properties like conductivity, work function or to some
5 extend viscosity can be measured.

In Fig 3b the helium particles have been deposited in the modification region 230 of the substrate 210 thereby causing a change in volume of at least the modification region 230 of the substrate. Other particles can be used to achieve this effect as well. In particular
10 any noble gas is well suited. In the embodiment shown in Fig 3b the volume of at least the modification region 230 has increased. This led to a change in the surface 215 of the substrate 210, in particular a swelling or rising of the substrate. This in turn led to a tilting of the structure 220 by an angle α so that the ROI 225 is now accessible to the measuring device 240. This angle α is defined as the angle between the surface normal of the ROI
15 225 before the moving of the structure 220 (shown as dashed arrow) and the surface normal of the ROI 225 after the moving of the structure 225 (shown in Fig 2b as a solid arrow).

Additionally the structure 220 has also been lifted in a direction perpendicular to the
20 reference surface plane 216. To make the ROI 225 accessible to the measuring device 240 a tilt of at least 45° , preferable 60° , more preferably 90° should be introduced. In addition to the tilting of a structure 220 the semiconductor article can be positioned in a semiconductor article holder and put on a semiconductor article stage. In the terminology of measuring devices the semiconductor article is here a sample to be measured. It is
25 preferred if the semiconductor article stage and/or the semiconductor article holder can be moved laterally and/or vertically. Additionally tilting capability of the semiconductor article stage and the semiconductor article holder are also preferable.

In the present embodiment the focused charged particle beam device 250 was used to
30 record an image of the semiconductor article, while modifying the substrate 210. This is advantageous because during deposition of the charged particles the positioning of the

charged particle beam 290 can be in-situ observed. If through the change in volume of the substrate 210 and the movement of the surface 215 the charged particle beam 290 is no longer focused on the modification region 230 the target can be adjusted. This is of particular advantage, if imaging and deposition is done with the same charged particle beam 290. Images can be stored in an image storage medium.

In the present embodiment the motion of the structures 220 also deformed the sidewalls of the structure 220 comprising the region of interest 225. This may have been caused by neighboring structures 220 colliding with the structure 220 comprising the ROI 225 or by another mechanism. A deformation of the ROI 225 will result in a new shape. That shape can be subtracted from the measured topographical map of the region of interest 225. Since the deformations will be in a complete different regime of spatial frequencies from the statistical variation (LER, LWR and the like) a subtraction of the new sidewall in the ROI 225 is possible.

Alternatively a further material correction step can be applied, where at least a part of the increased volume is removed using the charged particle beam device 250. In is advantageous to use the different particles for the volume removal from the particles used for the increase in volume of the modification region 230.

In this way some of the structures 220 that do not contain the ROI 225 can be removed, thus reducing the deformation of the sidewall of the structure 220 containing the ROI 225. Alternatively or additionally parts of the substrate 210 can also be removed. If necessary these steps can be repeated in an iteration until a sufficient result is reached.

The atomic force microscope 400 illustrated in figure 4 can be operated under ambient conditions or in a vacuum chamber (not illustrated in figure 4). The sample 410 to be analyzed is arranged on a sample stage 425. The sample stage 425 or the tip can be moved in three spatial directions by way of a scanning device 420. The scanning device 420 comprises for example one or more micro-displacement elements, for example in the form of piezo actuators (not shown in figure 4). The probe 455 or the measurement

probe 455 comprises a tip 430 or a measurement tip 430 and a cantilever 440 for the measurement tip 430.

The measurement tip 430 of the probe 455 can operate in a plurality of operating modes.

5 For one, it can be scanned over the surface 415 of the sample 410 at a constant height without feedback control. Alternatively, the probe 455 can be guided over the sample surface 415 with a constant force in a closed feedback loop. It is furthermore possible with the aid of a modulation method to make the cantilever 440 oscillate perpendicular to the sample surface 415 and as a result to scan the surface 415 of the sample 410 in a
10 closed feedback loop. Here, the cantilever 440 can oscillate at its resonant frequency or carry out a forced oscillation at a specified frequency. In the former case, i.e. the cantilever 440 or the probe 455 oscillates in frequency, a frequency modulation (FM) demodulation occurs, in which case the frequency change brought about by the interaction between the measurement tip 430 and the sample 410 is measured. In the case
15 of a forced oscillation near the resonant frequency, an amplitude modulation (AM) demodulation is carried out in order to detect the amplitude of the oscillation which is changed owing to the interaction between the measurement tip 430 and the sample surface 415.

20 In order to measure the deflection of the measurement tip 430 or of the cantilever 440 by the surface 415 of the sample 410, in one embodiment of the atomic force microscope 400, a laser system 460 directs a laser beam 465 onto the tip of the cantilever 440. The laser beam 465 which is reflected by the cantilever 440 is recorded by a photodetector 470. The photodetector 470 frequently has a four-quadrant configuration. As a result, it is
25 possible to not only measure a z-movement of the measurement tip 430 (i.e. perpendicular to the sample surface 415), but also a movement of the measurement tip 430 in the x-direction, i.e. pivoting of the tip 430. In the prior art, lateral forces occur mainly in contact mode, where the measurement tip 430 is guided over the sample 410 in contact with the surface 415. The lateral forces give an indication of the material of a just
30 examined sample surface 415.

Alternatively, an interferometer can be used to ascertain the pivoting of a measurement tip 430 (not shown in figure 4). Examples of interferometer types that can be used for this purpose are a Michelson interferometer or a Mach-Zehnder interferometer. In addition, a deflection of the measurement tip 430 can also be detected with the aid of piezoresistive elements or sensors of the cantilever 440 (not illustrated in figure 4). It is moreover also possible for the deflection of the measurement tip 430 to be determined from a combination of optical signals and the measurement data of piezoresistive elements (likewise not shown in figure 4).

- 10 Many types and modes of operation of an atomic force microscope 400 exist. As a possible improvement of the atomic force microscope 400 it furthermore has a control device 480. The latter is connected to a second laser system 490 by a supply line 484 for a control signal. In the example illustrated in figure 4, the laser beam 495 of the second laser system 490 is directed onto one of the arms or beams of the cantilever 440 of the probe 455 so as to bring about local heating of the beam or of the arm of the cantilever 440.
- 15

CLAIMS:

1. A Method for moving a structure (220) on a semiconductor article (180,410) comprising:
 - Providing a focused charged particle beam device (250)
 - 5 • Providing a semiconductor article (180,410) comprising a substrate (210), a surface (181,215,415) and a structure (220)
 - Defining a region of interest (225) on the structure (220)
 - Defining a modification region (230) in the substrate (210), where the modification region (230) is different from the region of interest (225)
 - 10 • Modifying the substrate (210) with the focused charged particle beam device (250) in the modification region (230) to move the structure (220).
2. Method according to claim 1, where the focused charged particle beam device (250) comprises a gas field ion microscope.
3. Method according to claim 2, where the gas comprises one of Helium, Neon,
15 Argon, Krypton or Xenon.
4. Method according to any of the preceding claims, further providing a measuring device (240) to measure a property of the structure (220).
5. Method according to claim 4 further comprising:
 - moving the structure (220), where the structure (220) comprises at least
20 one side not accessible to the measuring device (240) and a region of interest (225) that is at least partially located on this side, to a position, where the region of interest (225) is accessible to the measuring device and
 - measuring a property of the structure (220) in at least a part of the region
25 of interest (225).
6. Method according to claim 4 or 5 where the measured property is one of a line edge roughness (LER), line width roughness (LWR) or a two-dimensional topography.
7. Method according to claim 4 or 5 where moving the structure (220) comprises
30 tilting the structure (220) by an angle β .

8. Method according to claim 7 where the angle β is at least 45° .
9. Method according to any of the claims 4 to 8 where the measuring device (240) is one of a scanning probe microscope or an atomic force microscope.
10. Method according to one of the preceding claims where the substrate (210)
5 comprises a crystalline material.
11. Method according to claim 10 where the crystalline material comprises one of silicon, germanium, gallium nitride, gallium arsenide, silicon germanium, diamond, SiSiC.
12. Method according to one of the preceding claims further comprising depositing
10 particles of the focused charged particle beam device (250) in the modification region (230) of the substrate (210) thereby causing a change in volume of at least the modification region of the substrate (210).
13. Method according to claim 12 where the change in volume of at least the modification region (230) increases the volume of the modification region (230).
- 15 14. Method according to claim 12 where the change in volume of at least the modification region (230) decreases the volume of the modification region (230).
15. Method according to one of the preceding claims further comprising setting an angle α between a focused charged particle beam (290) and a reference surface plane (216) of the semiconductor article (180,410) to control the motion of the
20 structure (220).
16. Method according to one of the preceding claims further comprising setting a dwell time of a focused charge particle beam (290) on the modification region (230) of the substrate (210) to control the motion of the structure (220).
17. Method according to one of the preceding claims further comprising setting a spot
25 size of a focused charged particle beam (290) on the surface of the substrate (210) to control the motion of the structure (220).
18. Method according to one of the preceding claims further comprising cutting the semiconductor article (180,410) outside the region of interest (225) to guide the motion of the structure (220).

19. Method according to one of the preceding claims further comprising using the focused charged particle beam device (250) to record an image of the semiconductor article (180,410), while modifying the substrate (210).
20. Method according to claim 13 further comprising a material correction step,
5 where at least a part of the increased volume is removed using the charged particle beam device (250).
21. Method according to claim 20 where the particles used for the volume removal are different from the particles used for the increase in volume of the modification region (230).
- 10 22. Method according to claim 20 or 21 where multiple steps of increasing the volume of the modification region (230) and/or removing parts of increased volume are sequentially executed.
23. An inspection device for inspecting a semiconductor article (180,410) with a method according to one of the preceding claims comprising
15
 - A focused charged particle beam device (250)
 - A semiconductor article holder on a semiconductor article stage (425)
 - A measuring device (240)
 - An electronic control system (170) for the charged particle beam device (250)
- 20 24. An inspection device according to claim 23 where the focused charged particle beam device (250) is a focused ion beam device and the measuring device (240) is one of a scanning probe microscope or an atomic force microscope.
25. An inspection device according to claim 23 or 24 further comprising a scanning device for scanning the charged particle beam device (250).
- 25 26. An inspection device according to one of claim 23 to 25 where the semiconductor article stage (425) is tiltable and/or rotatable.
27. An inspection device according to one of claim 23 to 26 comprising an imaging unit connected to the focused charged particle beam device (250) for generation of images of the surface (181) of the substrate (210).
- 30 28. An inspection device according to one of claim 23 to 27 comprising a measurement collection unit connected to the measuring device.

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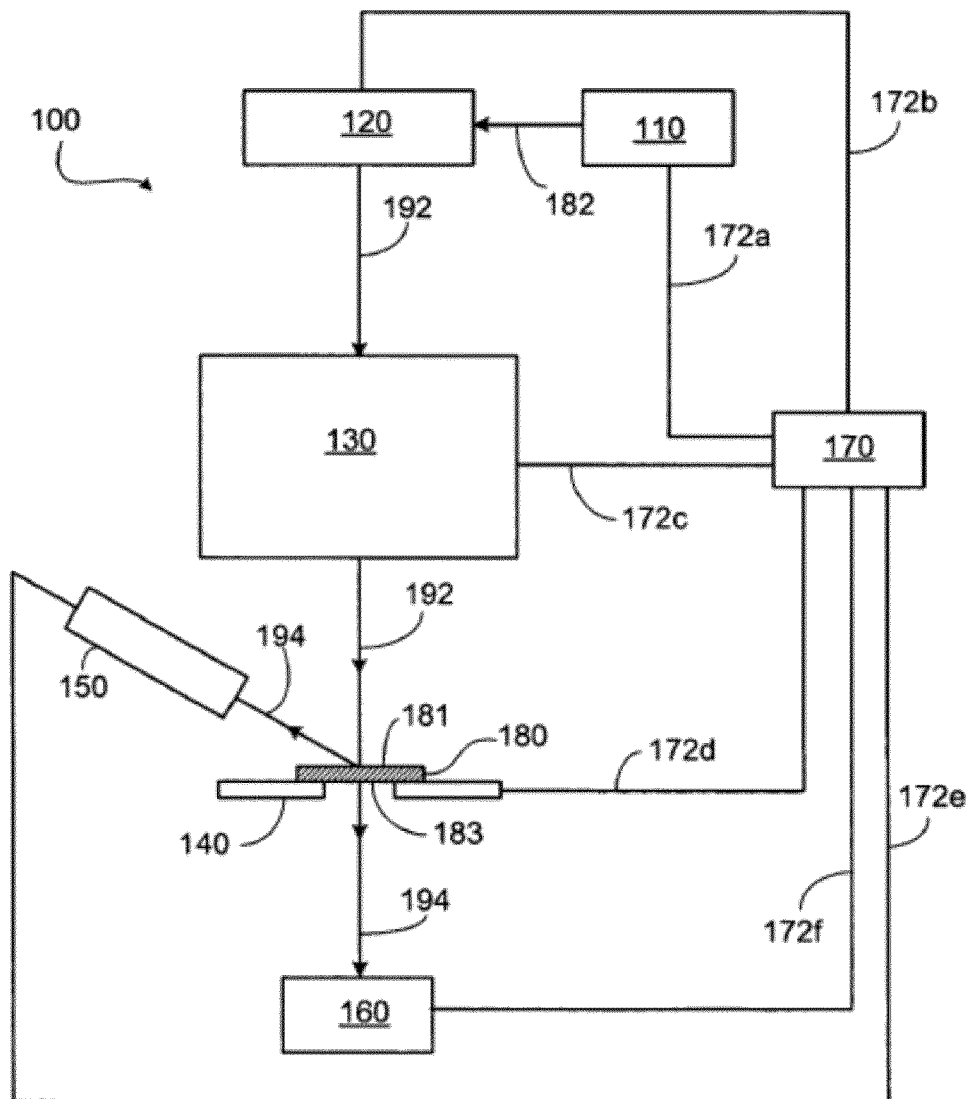
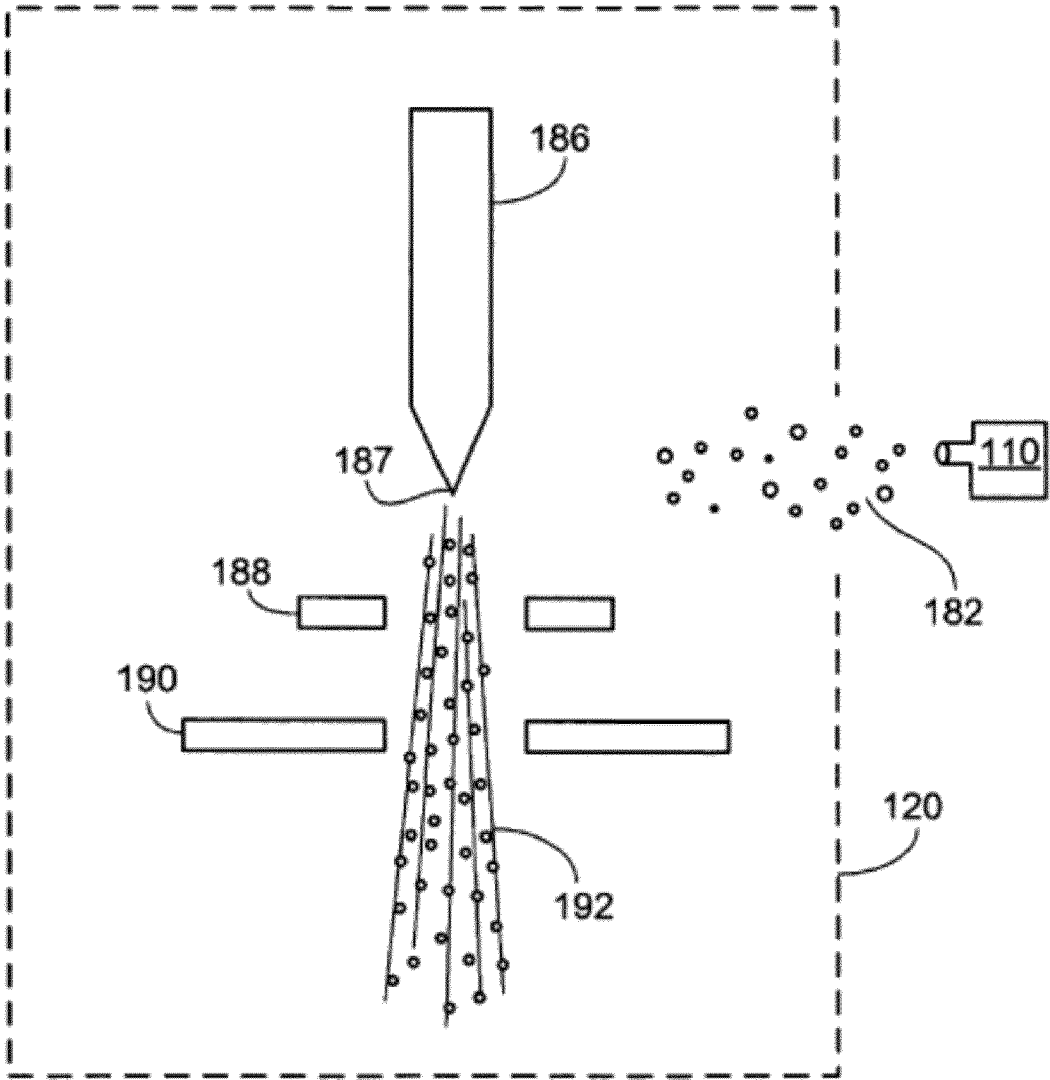
FIG.1

FIG.2



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FIG.3a

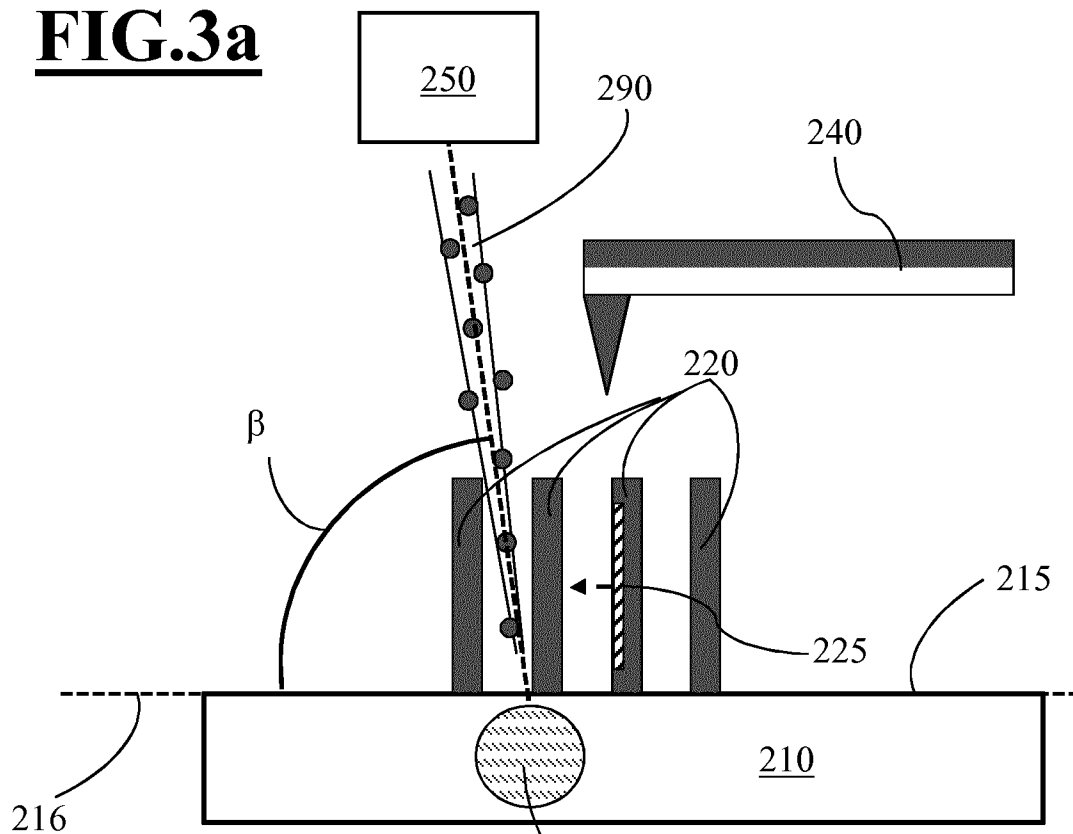
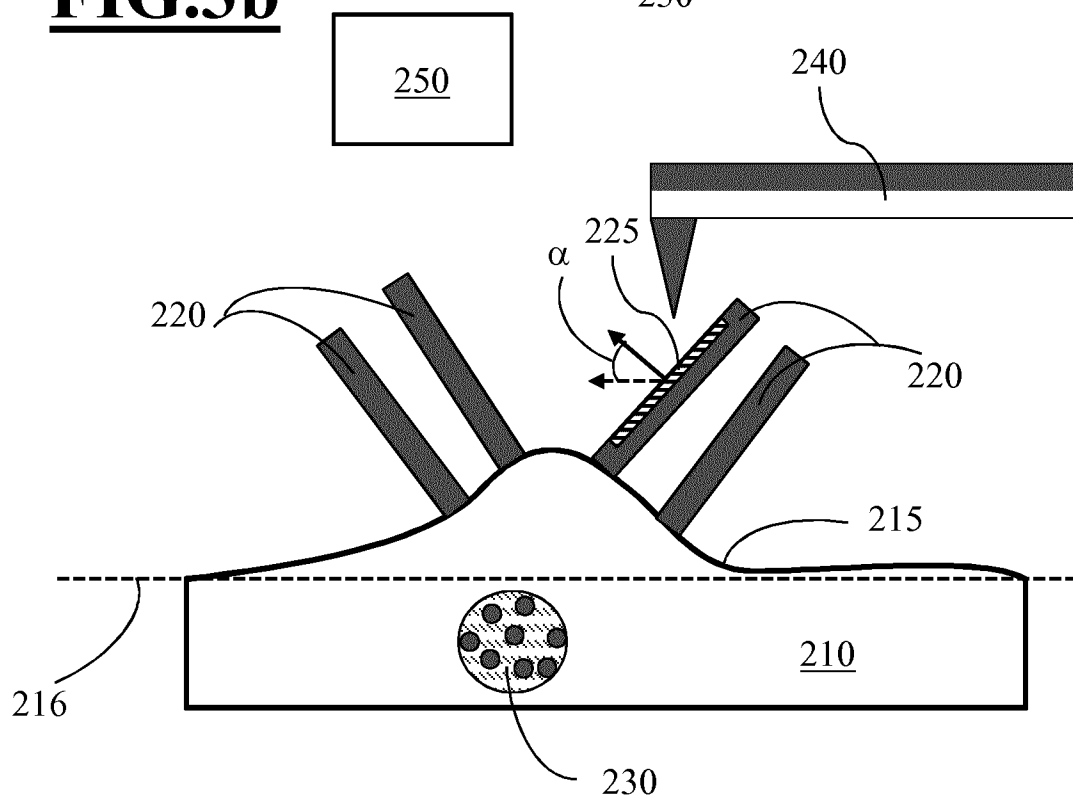
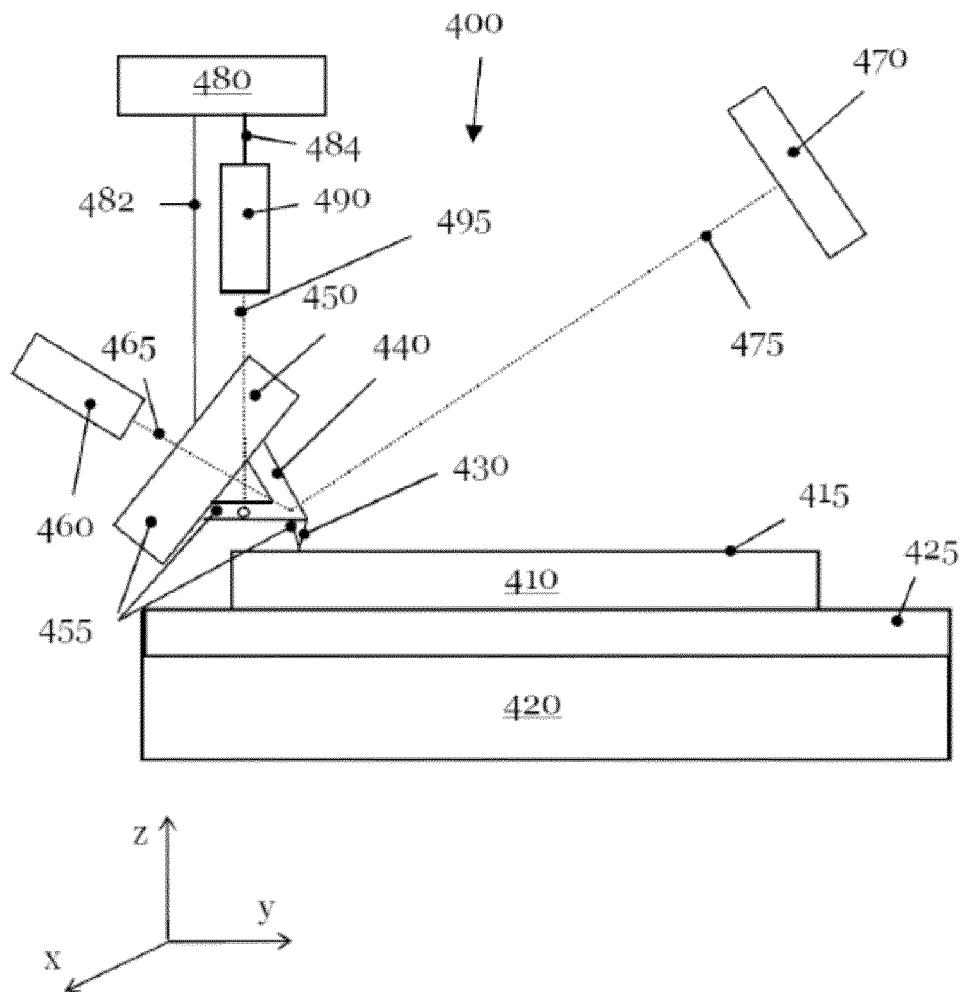


FIG.3b



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FIG.4

INTERNATIONAL SEARCH REPORT

International application No
PCT/EP2019/077927

A. CLASSIFICATION OF SUBJECT MATTER		
INV. G03F7/20	G01N23/225	H01J37/08
H01J37/317	H01L21/67	G03F1/72
ADD.		
According to International Patent Classification (IPC) or to both national classification and IPC		
B. FIELDS SEARCHED		
Minimum documentation searched (classification system followed by classification symbols) G03F G01N H01J H01L		
Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched		
Electronic data base consulted during the international search (name of data base and, where practicable, search terms used) EPO-Internal, WPI Data		
C. DOCUMENTS CONSIDERED TO BE RELEVANT		
Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 2017/287752 A1 (GODET LUDOVIC [US] ET AL) 5 October 2017 (2017-10-05)	1,4, 10-13, 15-17, 23,25-28
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☒ Further documents are listed in the continuation of Box C. ☒ See patent family annex.		
* Special categories of cited documents : "A" document defining the general state of the art which is not considered to be of particular relevance "E" earlier application or patent but published on or after the international filing date "L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified) "O" document referring to an oral disclosure, use, exhibition or other means "P" document published prior to the international filing date but later than the priority date claimed "T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention "X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone "Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art "&" document member of the same patent family		
Date of the actual completion of the international search 22 January 2020		Date of mailing of the international search report 04/02/2020
Name and mailing address of the ISA/ European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Fax: (+31-70) 340-3016		Authorized officer van Toledo, Wiebo

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Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
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