

DIRECTED MULTI-DEFLECTED ION BEAM MILLING OF A WORK PIECE AND
DETERMINING AND CONTROLLING EXTENT THEREOF

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FIELD AND BACKGROUND OF THE INVENTION

10 The present invention relates to ion beam milling of a work piece, and more particularly, to a method, device, and system, for directed multi-deflected ion beam milling of a work piece, and, determining and controlling extent thereof. The present invention is generally applicable in a wide variety of different fields, such as semiconductor manufacturing, micro-analytical testing, materials science, metrology, lithography,
15 micro-machining, and nanofabrication. The present invention is generally implementable in a wide variety of different applications of ion beam milling of a wide variety of different types of work pieces. The present invention is particularly implementable in a variety of different applications of preparing or/and analyzing a wide variety of different types of work pieces, particularly in the form of samples or materials, such as those derived from
20 semiconductor wafers or chips, that are widely used in the above indicated exemplary fields.

 Ion beam milling (etching) of a work piece (sample), directing an ion beam, deflecting an ion beam, and rotating an ion beam, theory, principles, and practices thereof, and, related and associated applications and subjects thereof, are well known and taught
25 about in the prior art, and currently widely practiced. For the purpose of establishing the scope, meaning, and field(s) of application, of the present invention, following are selected definitions and exemplary usages of terminology used for disclosing the present invention.

Work Piece

 Herein, in a non-limiting manner, work piece generally refers to any of a wide
30 variety of different types of materials, such as semiconductor materials, ceramic materials, pure metallic materials, metal alloy materials, polymeric materials, composite materials thereof, or materials derived therefrom.

For example, for a work piece being a semiconductor type of material, the work piece is typically in the form of a sample derived from a single die (of a wafer), a wafer segment, or a whole wafer. Ordinarily, such a work piece (sample) is pre-prepared using a micro-analytical sample preparation technique, for example, such as that disclosed in U.S. Provisional Patent Application No. 60/649,080, filed Feb. 03, 2005, entitled: "Sample Preparation For Micro-analysis", assigned to the present applicant/assignee. Pre-preparing the work piece (sample) using a micro-analytical sample preparation technique is based on 'sectioning' or 'segmenting' at least a part of the work piece (sample) precursor, via reducing or thinning at least one dimension (length, width, or/and thickness, depth or height) of the size of the work piece (sample) precursor, by using one or more types of a cutting, cleaving, slicing, or/and polishing, procedure, thereby producing a prepared work piece (sample) ready for subjection to another process, for example, ion beam milling. Such a prepared work piece (sample) has at least one dimension (length, width, or/and thickness, depth or height) in a range of between about 10 microns and about 50 microns, and another dimension in a range of between about 2 millimeters and about 3 millimeters.

Ion Beam Milling of a Work Piece

Ion beam milling of a work piece generally refers to impinging an ion beam onto a surface of the work piece, whereby interaction of the ion beam with the surface leads to removal of material from the surface, and therefore, from the work piece. In various fields, focused ion beam (FIB) milling and broad ion beam (BIB) milling are well known, taught about, and used, techniques of ion beam milling of a work piece. In general, focused ion beam (FIB) milling refers to a highly energetic, concentrated, and well focused, ion beam, originating from a liquid metal source, such as liquid gallium, which is incident and impinges upon, and mills, a surface of a work piece, whereby interaction of the focused ion beam with the surface leads to removal of material from the surface of the work piece. In general, broad ion beam (BIB) milling refers to a less energetic and less focused, broad ion beam, originating from an inert gas source, such as argon or xenon, which is incident and impinges upon, and mills, the surface of a work piece, whereby interaction of the broad ion beam with the surface leads to removal of material from the surface of the work piece.

In general, ion beam milling involving an ion beam incident and impinging upon a surface of a work piece, whereby interaction of the ion beam with the surface leads to a 'selective' type of removal of material from the surface, can be considered ion beam 'etching'. In the scope and context of the present invention, herein, ion beam milling

generally refers to an ion beam incident and impinging upon a surface of a work piece, whereby interaction of the ion beam with the surface leads to a non-selective, or a selective, type of removal of material from the surface of the work piece.

Directing an Ion Beam:

5 In the phrase 'directing an ion beam', the term 'directing' is generally equivalent to the synonymous terms guiding, regulating, controlling, and associated different grammatical forms thereof. Thus, directing an ion beam is generally equivalent to guiding, regulating, or controlling, an ion beam. In general, a directed, guided, regulated, or controlled, ion beam is directed, guided, regulated, or controlled, in or along a direction,
10 axis, path, or trajectory, toward an object, entity, or target, herein, generally referred to as a work piece. Such directing, guiding, regulating, or controlling, of an ion beam may be accomplished by a wide variety of different types of means which are well known, taught about, and used, in the prior art of ion beam and related technologies.

Deflecting an Ion Beam:

15 In the phrase 'deflecting an ion beam', the term 'deflecting' is generally equivalent to the synonymous terms swerving, turning aside, bending, deviating, or alternatively, to the synonymous phrases to cause to swerve, to cause to turn aside, to cause to bend, to cause to deviate, respectively, and associated different grammatical forms thereof. Thus, deflecting an ion beam is generally equivalent to swerving, turning aside, bending, or deviating, an
20 ion beam, or alternatively, causing an ion beam to swerve, turn aside, bend, or deviate, respectively, or alternatively, causing an ion beam to be swerved, turned aside, bent, or deviated, respectively, resulting in swerving, turning aside, bending, or deviating, respectively, of the ion beam. In general, an ion beam is deflected, caused to swerve, turned aside, bent, or deviated, from a first direction, path, axis, or trajectory, to a second
25 direction, path, axis, or trajectory, respectively. Such deflecting, causing to swerve, turning aside, bending, or deviating, of an ion beam may be accomplished by a wide variety of different types of means which are well known, taught about, and used, in the prior art of ion beam and related technologies.

Rotating an Ion Beam:

30 In the phrase 'rotating an ion beam', the term 'rotating' is generally equivalent to the synonymous terms turning or spinning on, around, or relative to, an axis, or alternatively, to the synonymous phrases to cause to turn, or to cause to spin, respectively, on, around, or relative to, an axis, and associated different grammatical forms thereof. Thus, rotating an

ion beam is generally equivalent to turning or spinning, an ion beam, on, around, or relative to, an axis, or alternatively, causing an ion beam to turn or spin, respectively, on, around, or relative to, an axis, or alternatively, causing an ion beam to be turned or spun, respectively, on, around, or relative to, an axis, resulting in turning or spinning, respectively, of the ion beam, on, around, or relative to, an axis.

In general, an ion beam is rotated (rotates), turned (turns), or spun (spins), on, around, or relative to, an axis, where the axis is either an axis of the ion beam, or an axis of an element or component which ordinarily shares the same spatial and temporal domains as the ion beam. Moreover, such rotating, turning, or spinning, of an ion beam on, around, or relative to, an axis, corresponds to angularly displacing the ion beam on, around, or relative to, the axis, where the axis is either an axis of the ion beam, or an axis of an element or component which ordinarily shares the same spatial and temporal domains as the ion beam.

Such rotating, turning, or spinning, of an ion beam, on, around, or relative to, an axis, may be accomplished by techniques known, taught about, and used, in the prior art of ion beam and related technologies. For example, by rotating, turning, or spinning, an ion beam source, such as a device or assembly which generates or produces the ion beam, on, around, or relative to, an axis, however, in such cases, it is significant to point out that the ion beam is stationary (static or fixed) relative to the ion beam source.

Fig. 1 is a schematic diagram illustrating a perspective view of an exemplary work piece, being a typical pre-prepared sample of a portion of a semiconductor wafer or chip having a surface (with a masking element), and selected features and parameters thereof, held by a sample holder element, where the sample is to be subjected to ion beam milling, for example, by implementing the present invention, for example, as part of preparing the sample for micro-analysis, or/and as part of analyzing the sample.

Implementation of prior art techniques of ion beam milling of a work piece is limited by an inability to simultaneously and automatically achieve the following four characteristics or aspects relating to preparing or/and analyzing a work piece: (1) thickness or thinness of a section of the work piece, (2) ability to locate a site specific target in a milled work piece, (3) depth of a site specific target within the work piece, and (4) quality of the milled surfaces of the work piece, including control of selectivity of the milled surfaces.

There is thus a need for, and it would be highly advantageous to have a method, device, and system, for directed multi-deflected ion beam milling of a work piece, and,

determining and controlling extent thereof. There is need for such an invention which is generally applicable in a wide variety of different fields, such as semiconductor manufacturing, micro-analytical testing, materials science, metrology, lithography, micro-machining, and nanofabrication. Moreover, there is need for such an invention which is generally implementable in a wide variety of different applications of ion beam milling of a wide variety of different types of work pieces. Additionally, there is need for such an invention which is particularly implementable in a variety of different applications of preparing or/and analyzing a wide variety of different types of work pieces, particularly in the form of samples or materials, such as those derived from semiconductor wafers or chips, that are widely used in the above indicated exemplary fields.

SUMMARY OF THE INVENTION

The present invention relates to ion beam milling of a surface, and more particularly, to a method, device, and system, for directed multi-deflected ion beam milling of a work piece, and, determining and controlling extent thereof. The present invention is generally applicable in a wide variety of different fields, such as semiconductor manufacturing, micro-analytical testing, materials science, metrology, lithography, micro-machining, and nanofabrication. The present invention is generally implementable in a wide variety of different applications of ion beam milling of a wide variety of different types of work pieces. The present invention is particularly implementable in a variety of different applications of preparing or/and analyzing a wide variety of different types of work pieces, particularly in the form of samples or materials, such as those derived from semiconductor wafers or chips, that are widely used in the above indicated exemplary fields.

Thus, according to the present invention, there is provided a method for directed multi-deflected ion beam milling of a work piece, comprising: providing an ion beam; and directing and at least twice deflecting the provided ion beam, for forming a directed multi-deflected ion beam, wherein the directed multi-deflected ion beam is directed towards, incident and impinges upon, and mills, a surface of the work piece.

According to another aspect of the present invention, there is provided a method for directed multi-deflecting a provided ion beam, comprising: directing and at least twice deflecting the provided ion beam, for forming a directed multi-deflected ion beam, by deflecting and directing the provided ion beam, for forming a directed once deflected ion

beam, and, deflecting and directing the directed once deflected ion beam, for forming a directed twice deflected ion beam being a type of the directed multi-deflected ion beam.

According to another aspect of the present invention, there is provided a device for directed multi-deflected ion beam milling of a work piece, comprising: an ion beam source assembly, for providing an ion beam; and an ion beam directing and multi-deflecting assembly, for directing and at least twice deflecting the provided ion beam, for forming a directed multi-deflected ion beam, wherein the directed multi-deflected ion beam is directed towards, incident and impinges upon, and mills, a surface of the work piece.

According to another aspect of the present invention, there is provided a device for directed multi-deflecting a provided ion beam, comprising: an ion beam directing and multi-deflecting assembly, for directing and at least twice deflecting the provided ion beam, for forming a directed multi-deflected ion beam, wherein the ion beam directing and multi-deflecting assembly includes an ion beam first deflecting assembly, for deflecting and directing the provided ion beam, for forming a directed once deflected ion beam, and an ion beam second deflecting assembly, for deflecting and directing the directed once deflected ion beam, for forming a directed twice deflected ion beam being a type of the directed multi-deflected ion beam.

According to another aspect of the present invention, there is provided a system for directed multi-deflected ion beam milling of a work piece, comprising: an ion beam unit, wherein the ion beam unit includes an ion beam source assembly, for providing an ion beam, and an ion beam directing and multi-deflecting assembly, for directing and at least twice deflecting the provided ion beam, for forming a directed multi-deflected ion beam, wherein the directed multi-deflected ion beam is directed towards, incident and impinges upon, and mills, a surface of the work piece; and a vacuum unit, operatively connected to the ion beam unit, for providing and maintaining a vacuum environment for the ion beam unit and the work piece, wherein the vacuum unit includes the work piece.

According to further characteristics in preferred embodiments of the invention described below, the system further includes electronics and process control utilities, operatively connected to the ion beam unit and to the vacuum unit, for providing electronics to, and enabling process control of, the ion beam unit and the vacuum unit.

According to further characteristics in preferred embodiments of the invention described below, the system further includes at least one additional unit selected from the group consisting of: a work piece imaging and milling detection unit, a work piece

manipulating and positioning unit, an anti-vibration unit, a component imaging unit, and at least one work piece analytical unit, wherein each additional unit is operatively connected to the vacuum unit.

According to another aspect of the present invention, there is provided a system for
5 directed multi-deflecting a provided ion beam, comprising: an ion beam unit, wherein the ion beam unit includes an ion beam directing and multi-deflecting assembly, for directing and at least twice deflecting the provided ion beam, for forming a directed multi-deflected ion beam, the ion beam directing and multi-deflecting assembly includes an ion beam first
10 deflecting assembly, for deflecting and directing the provided ion beam, for forming a directed once deflected ion beam, and an ion beam second deflecting assembly, for deflecting and directing the directed once deflected ion beam, for forming a directed twice deflected ion beam being a type of the multi-deflected ion beam; and a vacuum unit, operatively connected to the ion beam unit, for providing and maintaining a vacuum environment for the ion beam unit.

15 According to further characteristics in preferred embodiments of the invention described below, the system further includes electronics and process control utilities, operatively connected to the ion beam unit and to the vacuum unit, for providing electronics to, and enabling process control of, the ion beam unit and the vacuum unit.

According to further characteristics in preferred embodiments of the invention
20 described below, the system further includes at least one additional unit selected from the group consisting of: a work piece imaging and milling detection unit, a work piece manipulating and positioning unit, an anti-vibration unit, a component imaging unit, and at least one work piece analytical unit, wherein each additional unit is operatively connected to the vacuum unit.

25 According to another aspect of the present invention, there is provided a method for determining and controlling extent of ion beam milling of a work piece, comprising: providing a set of pre-determined values of at least one parameter of the work piece selected from the group consisting of: thickness of the work piece, depth of a target within the work piece, and topography of at least one surface of the work piece; performing
30 directed multi-deflected ion beam milling of the work piece using a method for the directed multi-deflected ion beam milling of a work piece, including the following main steps, and, components and functionalities thereof: providing an ion beam; and directing and at least twice deflecting the provided ion beam, for forming a directed multi-deflected ion beam,

wherein the directed multi-deflected ion beam is directed towards, incident and impinges upon, and mills, a surface of the work piece; real time measuring in-situ the at least one parameter of the work piece, for forming a set of measured values of the at least one parameter; comparing the set of the measured values to the provided set of the pre-determined values, for forming a set of value differences associated with the
5 comparing; feeding back the set of the value differences for continuing the performing directed multi-deflected ion beam milling of the work piece, until the value differences are within a pre-determined range.

According to further characteristics in preferred embodiments of the invention
10 described below, the degree of selectivity of the at least one surface of the work piece corresponds to the topography as being one of the pre-determined parameters of the work piece.

The present invention is implemented by performing procedures, steps, and sub-steps, in a manner selected from the group consisting of manually, semi-automatically, fully
15 automatically, and a combination thereof, involving use and operation of system units, system sub-units, devices, assemblies, sub-assemblies, mechanisms, structures, components, elements, and, peripheral equipment, utilities, accessories, and materials, in a manner selected from the group consisting of manually, semi-automatically, fully automatically, and a combination thereof. Moreover, according to actual procedures, steps, sub-steps, system
20 units, system sub-units, devices, assemblies, sub-assemblies, mechanisms, structures, components, elements, and, peripheral equipment, utilities, accessories, and materials, used for implementing a particular embodiment of the disclosed invention, the procedures, steps, and sub-steps, are performed by using hardware, software, or/and an integrated combination thereof, and the system units, system sub-units, devices, assemblies, sub-assemblies,
25 mechanisms, structures, components, elements, and, peripheral equipment, utilities, accessories, and materials, operate by using hardware, software, or/and an integrated combination thereof.

In particular, software used for implementing the present invention includes operatively connected and functioning written or printed data, in the form of software
30 programs, software routines, software sub-routines, software symbolic languages, software code, software instructions or protocols, software algorithms, or/and a combination thereof. Hardware used for implementing the present invention includes operatively connected and functioning electrical, electronic, magnetic, electromagnetic, electromechanical, and

optical, system units, system sub-units, devices, assemblies, sub-assemblies, mechanisms, structures, components, elements, and, peripheral equipment, utilities, accessories, and materials, which may include one or more computer chips, integrated circuits, electronic circuits, electronic sub-circuits, hard-wired electrical circuits, or/and combinations thereof, involving digital or/and analog operations. Accordingly, the present invention is implemented by using an integrated combination of the just described software and hardware.

BRIEF DESCRIPTION OF THE DRAWINGS

The present invention is herein described, by way of example only, with reference to the accompanying drawings. With specific reference now to the drawings in detail, it is stressed that the particulars shown are by way of example and for purposes of illustrative description of the preferred embodiments of the present invention only, and are presented in the cause of providing what is believed to be the most useful and readily understood description of the principles and conceptual aspects of the present invention. In this regard, no attempt is made to show structural details of the present invention in more detail than is necessary for a fundamental understanding of the invention, the description taken with the drawings making apparent to those skilled in the art how the several forms of the invention may be embodied in practice. In the drawings:

Fig. 1 is a schematic diagram illustrating a perspective view of an exemplary work piece, being a typical pre-prepared sample of a portion of a semiconductor wafer or chip having a surface (with a masking element), and selected features and parameters thereof, held by a sample holder element, where the sample is to be subjected to ion beam milling, for example, by implementing the present invention, for example, as part of preparing the sample for micro-analysis, or/and as part of analyzing the sample;

Fig. 2 is a schematic diagram illustrating a side view of an exemplary preferred embodiment of directed multi-deflected ion beam milling of a work piece, and, determining and controlling extent thereof, particularly showing the ion beam unit in relation to the work piece imaging and milling detection unit and the vacuum chamber assembly of the vacuum unit, and all these in relation to the work piece and a surface thereof, in accordance with the present invention;

Fig. 3 is a schematic diagram illustrating a side view of a more detailed version of the exemplary preferred embodiment illustrated in Fig. 2, particularly showing an

exemplary specific preferred embodiment of the device, being the ion beam unit, including the ion beam directing and multi-deflecting assembly, for *twice* deflecting an ion beam, and showing an exemplary specific preferred embodiment of the work piece imaging and milling detection unit, in accordance with the present invention;

5 Fig. 4 is a schematic diagram illustrating a side view of the directed multi-deflected ion beam milling of a work piece, and, determining and controlling extent thereof, illustrated in Figs. 2 and 3, particularly showing a cross-sectional side view of a more detailed component level version of the device, being the ion beam unit, including the ion beam directing and multi-deflecting assembly, structured and functional for *twice*
10 deflecting an ion beam, in accordance with the present invention;

Fig. 5 is a schematic diagram illustrating a perspective view of the directed multi-deflected ion beam milling of a work piece, illustrated in Figs. 2, 3, and 4, particularly showing an exemplary specific preferred embodiment of each of the ion beam first deflecting assembly and the ion beam second deflecting assembly, included in the ion
15 beam directing and multi-deflecting assembly of the ion beam unit, structured and functional for *twice* deflecting an ion beam, in accordance with the present invention;

Figs. 6a - 6e are schematic diagrams together illustrating a perspective view of a rotational (angular) sequence of an ion beam directed and multi-deflected, relative to an arbitrarily assigned longitudinal axis coaxial with the work piece, by the first ion beam
20 deflecting assembly and the second ion beam deflecting assembly, corresponding to a directed twice deflected ion beam type of directed multi-deflected ion beam which rotates in a range of between 0° and 360° around the longitudinal axis, and is directed towards, incident and impinges upon, and mills, a surface of the work piece, in accordance with the present invention;

25 Fig. 7a is a schematic diagram illustrating a perspective close-up view of a directed multi-deflected (*twice* or *thrice* deflected) ion beam directed towards, incident and impinging upon, and milling, a surface of a first type of an exemplary work piece (a generally shaped rectangular slab), particularly showing relative geometries and dimensions of the ion beam, the surface, and the work piece, in accordance with the present
30 invention;

Fig. 7b is a schematic diagram illustrating a perspective close-up view of a directed multi-deflected (*twice* or *thrice* deflected) ion beam directed towards, incident and impinging upon, and milling, a surface of a second type of an exemplary work piece (a

typical sample of a portion of a semiconductor wafer or chip wherein the surface (with a mask) is held by a sample holder element, for example, similar to that illustrated in Fig. 1), particularly showing relative geometries and dimensions of the ion beam, the surface, and the work piece, in accordance with the present invention;

5 Fig. 8 is a schematic diagram illustrating a side view of a more detailed version of the exemplary preferred embodiment illustrated in Fig. 2, particularly showing an exemplary specific preferred embodiment of the ion beam unit, including the ion beam directing and multi-deflecting assembly, for *thrice* deflecting an ion beam, and an exemplary specific preferred embodiment of the work piece imaging and milling detection
10 unit, in accordance with the present invention;

 Fig. 9 is a schematic diagram illustrating a side view of the directed multi-deflected ion beam milling of a work piece, and, determining and controlling extent thereof, illustrated in Figs. 2 and 8, particularly showing a cross-sectional side view of a more detailed component level version of the ion beam unit, including the ion beam directing
15 and multi-deflecting assembly, structured and functional for *twice* deflecting an ion beam, in accordance with the present invention;

 Fig. 10 is a schematic diagram illustrating a perspective view of the directed multi-deflected ion beam milling of a work piece, illustrated in Figs. 2, 8, and 9, particularly showing an exemplary specific preferred embodiment of each of the ion beam
20 first deflecting assembly, the ion beam second deflecting assembly, and the ion beam third deflecting assembly, included in the ion beam directing and multi-deflecting assembly of the ion beam unit, structured and functional for *thrice* deflecting an ion beam, in accordance with the present invention;

 Fig. 11 is a block diagram illustrating an exemplary preferred embodiment of the
25 system for directed multi-deflected ion beam milling of a work piece, including the ion beam unit and a vacuum unit, and various possible specific exemplary preferred embodiments thereof, by further including at least one additional unit selected from the group consisting of: a work piece imaging and milling detection unit, a work piece manipulating and positioning unit, an anti-vibration unit, a component imaging unit, and a
30 work piece analytical unit, in accordance with the present invention;

 Fig. 12 is an (isometric) schematic diagram illustrating a perspective view of the system, and additional units thereof, for directed multi-deflected ion beam milling of a work piece, illustrated in Fig. 11, in accordance with the present invention;

Fig. 13 is an (isometric) schematic diagram illustrating a top view of the system illustrated in Figs. 11 and 12, in accordance with the present invention;

Fig. 14 is an (isometric) schematic diagram illustrating a perspective view of an exemplary specific preferred embodiment of the work piece imaging and milling detection unit, and main components thereof, in relation to the ion beam unit, the work piece manipulating and positioning unit, the component imaging unit, and all these in relation to the work piece, as part of the system illustrated in Figs. 12 and 13, in accordance with the present invention;

Fig. 15 is an (isometric) schematic diagram illustrating a perspective view of an exemplary specific preferred embodiment of the work piece manipulating and positioning unit, and main components thereof, particularly showing close-up views of the work piece holder assembly without a work piece (a), and with a work piece (b), as part of the system illustrated in Figs. 12 and 13, in accordance with the present invention;

Fig. 16 is a schematic diagram illustrating a combined cross-section view (upper part (a)) and top view (lower part (b)) of using the exemplary specific preferred embodiment of the work piece imaging and milling detection unit, and main components thereof, along with the ion beam unit, and the work piece manipulating and positioning unit, as part of the system illustrated in Figs. 11, 12, and 13, in relation to the work piece, illustrated in Fig. 14, for determining and controlling extent of ion beam milling of a work piece, in accordance with the present invention; and

Figs. 17a and 17b are schematic diagrams illustrating a cross-section view of determining depth of a target within a milled work piece, as part of determining and controlling extent of ion beam milling of a work piece, using the transmitted electron detector assembly included in the work piece imaging and milling detection unit illustrated in Figs. 14 and 16, in accordance with the present invention.

DESCRIPTION OF THE PREFERRED EMBODIMENTS

The present invention relates to ion beam milling of a surface, and more particularly, to a method, device, and system, for directed multi-deflected ion beam milling of a work piece, and, determining and controlling extent thereof. The present invention is generally applicable in a wide variety of different fields, such as semiconductor manufacturing, micro-analytical testing, materials science, metrology, lithography, micro-machining, and nanofabrication. The present invention is generally implementable

in a wide variety of different applications of ion beam milling of a wide variety of different types of work pieces. The present invention is particularly implementable in a variety of different applications of preparing or/and analyzing a wide variety of different types of work pieces, particularly in the form of samples or materials, such as those derived from semiconductor wafers or chips, that are widely used in the above indicated exemplary fields.

A main aspect of the present invention is provision of a method for directed multi-deflected ion beam milling of a work piece, including the following main steps, and, components and functionalities thereof: providing an ion beam; and directing and at least twice deflecting the provided ion beam, for forming a directed multi-deflected ion beam, wherein the directed multi-deflected ion beam is directed towards, incident and impinges upon, and mills, a surface of the work piece.

Another main aspect of the present invention is a sub-combination of the method for directed multi-deflected ion beam milling of a work piece, whereby there is provision of a method for directed multi-deflecting a provided ion beam, including the following main steps, and, components and functionalities thereof: directing and at least twice deflecting the provided ion beam, for forming a directed multi-deflected ion beam, by deflecting and directing the provided ion beam, for forming a directed once deflected ion beam, and, deflecting and directing the directed once deflected ion beam, for forming a directed twice deflected ion beam being a type of the directed multi-deflected ion beam.

Another main aspect of the present invention is provision of a device for directed multi-deflected ion beam milling of a work piece, including the following main components and functionalities thereof: an ion beam source assembly, for providing an ion beam; and an ion beam directing and multi-deflecting assembly, for directing and at least twice deflecting the provided ion beam, for forming a directed multi-deflected ion beam, wherein the directed multi-deflected ion beam is directed towards, incident and impinges upon, and mills, a surface of the work piece.

Another main aspect of the present invention is a sub-combination of the device for directed multi-deflected ion beam milling of a work piece, whereby there is provision of a device for directed multi-deflecting a provided ion beam, including the following main components and functionalities thereof: an ion beam directing and multi-deflecting assembly, for directing and at least twice deflecting the provided ion beam, for forming a directed multi-deflected ion beam, wherein the ion beam directing and multi-deflecting

assembly includes an ion beam first deflecting assembly, for deflecting and directing the provided ion beam, for forming a directed once deflected ion beam, and an ion beam second deflecting assembly, for deflecting and directing the directed once deflected ion beam, for forming a directed twice deflected ion beam being a type of the directed multi-deflected ion beam.

Another main aspect of the present invention is provision of a system for directed multi-deflected ion beam milling of a work piece, including the following main components and functionalities thereof: an ion beam unit, wherein the ion beam unit includes an ion beam source assembly, for providing an ion beam, and an ion beam directing and multi-deflecting assembly, for directing and at least twice deflecting the provided ion beam, for forming a directed multi-deflected ion beam, wherein the directed multi-deflected ion beam is directed towards, incident and impinges upon, and mills, a surface of the work piece; and a vacuum unit, operatively connected to the ion beam unit, for providing and maintaining a vacuum environment for the ion beam unit and the work piece. Preferably, the vacuum unit includes the work piece.

Preferably, the system further includes electronics and process control utilities, operatively connected to the ion beam unit and to the vacuum unit, for providing electronics to, and enabling process control of, the ion beam unit and the vacuum unit. Optionally, and preferably, the system further includes at least one additional unit selected from the group consisting of: a work piece imaging and milling detection unit, a work piece manipulating and positioning unit, an anti-vibration unit, a component imaging unit, and at least one work piece analytical unit, wherein each additional unit is operatively connected to the vacuum unit. Preferably, the electronics and process control utilities is also operatively connected to each additional unit, for providing electronics to, and enabling process control of, each additional unit, in a manner operatively integrated with the ion beam unit and the vacuum unit.

Another main aspect of the present invention is a sub-combination of the system for directed multi-deflected ion beam milling of a work piece, whereby there is provision of a system for directed multi-deflecting a provided ion beam, including the following main components and functionalities thereof: an ion beam unit, wherein the ion beam unit includes an ion beam directing and multi-deflecting assembly, for directing and at least twice deflecting the provided ion beam, for forming a directed multi-deflected ion beam, the ion beam directing and multi-deflecting assembly includes an ion beam first deflecting

assembly, for deflecting and directing the provided ion beam, for forming a directed once deflected ion beam, and an ion beam second deflecting assembly, for deflecting and directing the directed once deflected ion beam, for forming a directed twice deflected ion beam being a type of the multi-deflected ion beam; and an ion beam second deflecting
5 assembly, for deflecting and directing the directed once deflected ion beam, for forming a directed twice deflected ion beam being a type of the multi-deflected ion beam; and a vacuum unit, operatively connected to the ion beam unit, for providing and maintaining a vacuum environment for the ion beam unit.

Preferably, the system further includes electronics and process control utilities,
10 operatively connected to the ion beam unit and to the vacuum unit, for providing electronics to, and enabling process control of, the ion beam unit and the vacuum unit. Optionally, and preferably, the system further includes at least one additional unit selected from the group consisting of: a work piece imaging and milling detection unit, a work piece manipulating and positioning unit, an anti-vibration unit, a component imaging unit,
15 and at least one work piece analytical unit, wherein each additional unit is operatively connected to the vacuum unit. Preferably, the electronics and process control utilities is also operatively connected to each additional unit, for providing electronics to, and enabling process control of, each additional unit, in a manner operatively integrated with the ion beam unit and the vacuum unit.

Another main aspect of the present invention is provision of a method for
20 determining and controlling extent of ion beam milling of a work piece, including the following main steps, and, components and functionalities thereof: providing a set of pre-determined values of at least one parameter of the work piece selected from the group consisting of: thickness of the work piece, depth of a target within the work piece, and
25 topography of at least one surface of the work piece; performing directed multi-deflected ion beam milling of the work piece using a method for the directed multi-deflected ion beam milling of a work piece, including the following main steps, and, components and functionalities thereof: providing an ion beam; and directing and at least twice deflecting the provided ion beam, for forming a directed multi-deflected ion beam, wherein the
30 directed multi-deflected ion beam is directed towards, incident and impinges upon, and mills, a surface of the work piece; real time measuring in-situ the at least one parameter of the work piece, for forming a set of measured values of the at least one parameter; comparing the set of the measured values to the provided set of the pre-determined values,

for forming a set of value differences associated with the comparing; feeding back the set of the value differences for continuing the performing directed multi-deflected ion beam milling of the work piece, until the value differences are within a pre-determined range.

5 In the method, the degree of selectivity of the at least one surface of the work piece corresponds to the topography as being one of the pre-determined parameters of the work piece.

Accordingly, the present invention is based on a unique method, device, and system, and sub-combinations thereof, for directed multi-deflected ion beam milling of a work piece, and, determining and controlling extent thereof.

10 It is to be understood that the present invention is not limited in its application to the details of the order or sequence, and number, of procedures, steps, and sub-steps, of operation or implementation, or to the details of type, composition, construction, arrangement, order, and number, of the system units, sub-units, devices, assemblies, sub-assemblies, mechanisms, structures, components, elements, and, peripheral equipment,
15 utilities, accessories, and materials, set forth in the following illustrative description and accompanying drawings, *unless otherwise specifically stated herein*. The present invention is capable of other embodiments and of being practiced or carried out in various ways. Although procedures, steps, sub-steps, and system units, sub-units, devices, assemblies, sub-assemblies, mechanisms, structures, components, elements, and, peripheral equipment,
20 utilities, accessories, and materials, similar or equivalent to those illustratively described herein can be used for practicing or testing the present invention, suitable procedures, steps, sub-steps, and system units, sub-units, devices, assemblies, sub-assemblies, mechanisms, structures, components, elements, and, peripheral equipment, utilities, accessories, and materials, are illustratively described herein.

25 It is also to be understood that all technical and scientific words, terms, or/and phrases, used herein throughout the present disclosure have either the identical or similar meaning as commonly understood by one of ordinary skill in the art to which this invention belongs, *unless otherwise specifically defined or stated herein*. Phraseology, terminology, and, notation, employed herein throughout the present disclosure are for the purpose of
30 description and should not be regarded as limiting. It is to be fully understood that, unless specifically stated otherwise, the phrase 'operatively connected' is generally used herein, and equivalently refers to the corresponding synonymous phrases 'operatively joined', and 'operatively attached', where the operative connection, operative joint, or operative

attachment is according to a physical, or/and electrical, or/and electronic, or/and mechanical, or/and electro-mechanical, manner or nature, involving various types and kinds of hardware or/and software equipment and components. Moreover, all technical and scientific words, terms, or/and phrases, introduced, defined, described, or/and exemplified, in the above Background section, are equally or similarly applicable in the illustrative description of the preferred embodiments, examples, and appended claims, of the present invention.

In particular, in the scope and context of the present invention, with respect to the phrase 'work piece', herein, in a non-limiting manner, work piece generally refers to any of a wide variety of different types of materials, such as semiconductor materials, ceramic materials, pure metallic materials, metal alloy materials, polymeric materials, composite materials thereof, or materials derived therefrom.

For example, for a work piece being a semiconductor type of material, the work piece is typically in the form of a sample derived from a single die (of a wafer), a wafer segment, or a whole wafer. Ordinarily, such a work piece (sample) is pre-prepared using a micro-analytical sample preparation technique, for example, such as that disclosed in U.S. Provisional Patent Application No. 60/649,080, filed Feb. 03, 2005, entitled: "Sample Preparation For Micro-analysis", assigned to the present applicant/assignee. Pre-preparing the work piece (sample) using a micro-analytical sample preparation technique is based on 'sectioning' or 'segmenting' at least a part of the work piece (sample) precursor, via reducing or thinning at least one dimension (length, width, or/and thickness, depth or height) of the size of the work piece (sample) precursor, by using one or more types of a cutting, cleaving, slicing, or/and polishing, procedure, thereby producing a prepared work piece (sample) ready for subjection to another process, for example, ion beam milling. Such a prepared work piece (sample) has at least one dimension (length, width, or/and thickness, depth or height) in a range of between about 10 microns and about 50 microns, and another dimension in a range of between about 2 millimeters and about 3 millimeters.

In particular, with respect to the phrase 'ion beam milling of a work piece', herein, ion beam milling of a work piece generally refers to impinging an ion beam onto a surface of the work piece, whereby interaction of the ion beam with the surface leads to removal of material from the surface, and therefore, from the work piece. In general, focused ion beam (FIB) milling refers to a highly energetic, concentrated, and well focused, ion beam, originating from a liquid metal source, such as liquid gallium, which is incident and

impinges upon, and mills, a surface of a work piece, whereby interaction of the focused ion beam with the surface leads to removal of material from the surface of the work piece. In general, broad ion beam (BIB) milling refers to a less energetic and less focused, broad ion beam, originating from an inert gas source, such as argon or xenon, which is incident and
5 impinges upon, and mills, the surface of a work piece, whereby interaction of the broad ion beam with the surface leads to removal of material from the surface of the work piece.

In general, ion beam milling involving an ion beam incident and impinging upon a surface of a work piece, whereby interaction of the ion beam with the surface leads to a 'selective' type of removal of material from the surface, can be considered ion beam
10 'etching'. In the scope and context of the present invention, herein, ion beam milling generally refers to an ion beam incident and impinging upon a surface of a work piece, whereby interaction of the ion beam with the surface leads to a non-selective, or a selective, type of removal of material from the surface of the work piece.

In particular, with respect to the phrase 'directing an ion beam', the term 'directing'
15 is generally equivalent to the synonymous terms guiding, regulating, controlling, and associated different grammatical forms thereof. Thus, directing an ion beam is generally equivalent to guiding, regulating, or controlling, an ion beam. In general, a directed, guided, regulated, or controlled, ion beam is directed, guided, regulated, or controlled, in or along a direction, path, axis, or trajectory, toward an object, entity, or target, herein,
20 generally referred to as a work piece.

In particular, with respect to the phrase 'deflecting an ion beam', the term 'deflecting' is generally equivalent to the synonymous terms swerving, turning aside, bending, deviating, or alternatively, to the synonymous phrases to cause to swerve, to cause to turn aside, to cause to bend, to cause to deviate, respectively, and associated
25 different grammatical forms thereof. Thus, deflecting an ion beam is generally equivalent to swerving, turning aside, bending, or deviating, an ion beam, or alternatively, causing an ion beam to swerve, turn aside, bend, or deviate, respectively, or alternatively, causing an ion beam to be swerved, turned aside, bent, or deviated, respectively, resulting in swerving, turning aside, bending, or deviating, respectively, of the ion beam. In general, an ion beam
30 is deflected, caused to swerve, turned aside, bent, or deviated, from a first direction, path, axis, or trajectory, to a second direction, path, axis, or trajectory, respectively.

Accordingly, based on the preceding description, meaning, and understanding, of the phrase 'deflecting an ion beam', herein, the phrase 'multi-deflecting an ion beam'

generally refers to deflecting an ion beam more than once, in particular, at least twice, and in general, any number of times more than once, corresponding to a plurality or multiple of times, thus, the term 'multi-deflecting'. As a first specific example or embodiment of the present invention, deflecting an ion beam two times or twice, is herein referred to by the phrase 'twice deflecting an ion beam'. As a second specific example or embodiment of the present invention, deflecting an ion beam three times or thrice, is herein referred to by the phrase 'thrice deflecting an ion beam'. Thus, in general, for describing the present invention, deflecting an ion beam at least two times, is herein referred to by the phrase 'at least twice deflecting an ion beam', or, equivalently, 'multi-deflecting an ion beam'. It is to be fully understood that the present invention is not at all limited to multi-deflecting an ion beam by twice or thrice deflecting the ion beam. In general, the present invention can be implemented wherein multi-deflecting an ion beam involves deflecting the ion beam more than three times, more than four times, etc..

In a corresponding manner, herein, the phrase 'multi-deflected ion beam' refers to an ion beam deflected more than once, in particular, at least twice, and in general, any number of times more than once, corresponding to a plurality or multiple of times, thus, the term 'multi-deflected'. As a corresponding first specific example or embodiment of the present invention, an ion beam deflected two times or twice, is herein referred to by the phrase 'twice deflected ion beam'. As a corresponding second specific example or embodiment of the present invention, an ion beam deflected three times or thrice, is herein referred to by the phrase 'thrice deflected ion beam'. Thus, in a corresponding manner, in general, for describing the present invention, an ion beam deflected at least two times, is herein referred to by the phrase 'multi-deflected ion beam', being equivalent to the phrase 'at least twice deflected ion beam'. It is to be fully understood that the present invention is not at all limited to a multi-deflected ion beam being a twice or thrice deflected ion beam. In general, the present invention can be implemented wherein a multi-deflected ion beam is an ion beam deflected more than three times, more than four times, etc..

Accordingly, based on the preceding description, meaning, and understanding, of the phrases 'directing an ion beam' and 'deflecting an ion beam', herein, the phrase 'directing and at least twice deflecting an ion beam' generally refers to directing an ion beam before, during, and after, being deflected more than once, in particular, at least twice, and in general, any number of times more than once. As a first specific example or embodiment of the present invention, directing an ion beam, followed by deflecting the

directed ion beam two times or twice, and then directing the twice deflected ion beam, is herein referred to by the phrase 'directing and at least twice deflecting an ion beam'. As a second specific example or embodiment of the present invention, directing an ion beam, followed by deflecting the directed ion beam three times or thrice, is herein referred to by the phrase 'directing and thrice deflecting an ion beam'. Thus, in general, for describing the present invention, deflecting an ion beam at least two times, is herein referred to by the phrase 'directing and at least twice deflecting an ion beam', or, equivalently, 'directing and multi-deflecting an ion beam'. It is to be fully understood that the present invention is not at all limited to directing and multi-deflecting an ion beam by directing and twice or thrice deflecting the ion beam. In general, the present invention can be implemented wherein directing and multi-deflecting an ion beam involves directing and deflecting the ion beam more than three times, more than four times, etc..

In a corresponding manner, herein, the phrase 'directed multi-deflected ion beam' refers to an ion beam which is directed before, during, and after, being deflected more than once, in particular, at least twice, and in general, any number of times more than once, corresponding to a plurality or multiple of times, thus, the phrase 'directed multi-deflected'.

As a corresponding first specific example or embodiment of the present invention, an ion beam directed before, during, and after, being deflected two times or twice, is herein referred to by the phrase 'directed twice deflected ion beam'. As a corresponding second specific example or embodiment of the present invention, an ion beam directed before, during, and after, being deflected three times or thrice, is herein referred to by the phrase 'directed thrice deflected ion beam'. Thus, in a corresponding manner, in general, for describing the present invention, an ion beam directed before, during, and after, being deflected at least two times, is herein referred to by the phrase 'directed multi-deflected ion beam', being equivalent to the phrase 'directed at least twice deflected ion beam'. It is to be fully understood that the present invention is not at all limited to a directed multi-deflected ion beam being a directed twice or thrice deflected ion beam. In general, the present invention can be implemented wherein a directed multi-deflected ion beam is an ion beam directed before, during, and after, being deflected more than three times, more than four times, etc..

In particular, with respect to the phrase 'rotating a directed multi-deflected (at least twice deflected) ion beam', herein, the term 'rotating' is generally equivalent to the synonymous terms turning or spinning on, around, or relative to, an axis, or alternatively,

to the synonymous phrases to cause to turn, or to cause to spin, respectively, on, around, or relative to, an axis, and associated different grammatical forms thereof. Thus, rotating a directed multi-deflected (at least twice deflected) ion beam is generally equivalent to turning or spinning, a directed multi-deflected (at least twice deflected) ion beam, on, around, or relative to, an axis, or alternatively, causing a directed multi-deflected (at least twice deflected) ion beam to turn or spin, respectively, on, around, or relative to, an axis, or alternatively, causing a directed multi-deflected (at least twice deflected) ion beam to be turned or spun, respectively, on, around, or relative to, an axis, resulting in turning or spinning, respectively, of the directed multi-deflected (at least twice deflected) ion beam, on, around, or relative to, an axis.

In general, a directed multi-deflected (at least twice deflected) ion beam is rotated (rotates), turned (turns), spun (spins), on, around, or relative to, an axis, where the axis is either an axis of the ion beam, or an axis of an element or component which ordinarily shares the same spatial and temporal domains as the ion beam. Moreover, such rotating, turning, or spinning, of a directed multi-deflected (at least twice deflected) ion beam on, around, or relative to, an axis, corresponds to angularly displacing the directed multi-deflected (at least twice deflected) ion beam on, around, or relative to, an axis, where the axis is either an axis of the ion beam, or an axis of an element or component which ordinarily shares the same spatial and temporal domains as the ion beam.

Additionally, as used herein, the term 'about' refers to $\pm 10\%$ of the associated value.

Procedures, steps, sub-steps, system units, system sub-units, devices, assemblies, sub-assemblies, mechanisms, structures, components, and elements, and, peripheral equipment, utilities, accessories, and materials, as well as operation and implementation, of exemplary preferred embodiments, alternative preferred embodiments, specific configurations, and, additional and optional aspects, characteristics, or features, thereof, of the present invention, are better understood with reference to the following illustrative description and accompanying drawings. Throughout the following illustrative description and accompanying drawings, same reference numbers, and letters, refer to same system units, sub-units, devices, assemblies, sub-assemblies, mechanisms, structures, components, and elements, and, peripheral equipment, utilities, accessories, and materials.

In the following illustrative description of the present invention, included are main or principal procedures, steps, and sub-steps, and, main or principal system units, system

sub-units, devices, assemblies, sub-assemblies, mechanisms, structures, components, and elements, and, peripheral equipment, utilities, accessories, and materials, needed for sufficiently understanding proper 'enabling' utilization and implementation of the disclosed invention. Accordingly, description of various possible preliminary, intermediate, minor, or/and optional, procedures, steps, or/and sub-steps, or/and, system units, system sub-units, devices, assemblies, sub-assemblies, mechanisms, structures, components, and elements, and, peripheral equipment, utilities, accessories, and materials, of secondary importance with respect to enabling implementation of the invention, which are readily known by one of ordinary skill in the art, or/and which are available in the prior art and technical literature relating to the invention, are at most only briefly indicated herein.

In the following illustrative description of the present invention, in a non-limiting manner, the general order of presentation is as follows: the method for directed multi-deflected ion beam milling of a work piece; the method for directed multi-deflecting a provided ion beam, as a sub-combination of the method for directed multi-deflected ion beam milling of a work piece; the device for directed multi-deflected ion beam milling of a work piece; the device for directed multi-deflecting a provided ion beam, as a sub-combination of the device for directed multi-deflected ion beam milling of a work piece; the system for directed multi-deflected ion beam milling of a work piece; the system for directed multi-deflecting a provided ion beam, as a sub-combination of the system for directed multi-deflected ion beam milling of a work piece; and the method for determining and controlling extent of ion beam milling of a work piece.

Thus, a main aspect of the present invention is provision of a method for directed multi-deflected ion beam milling of a work piece, including the following main steps, and, components and functionalities thereof: providing an ion beam; and directing and at least twice deflecting the provided ion beam, for forming a directed multi-deflected ion beam, wherein the directed multi-deflected ion beam is directed towards, incident and impinges upon, and mills, a surface of the work piece.

Referring now to the drawings, Fig. 2 is a schematic diagram illustrating a side view of an exemplary preferred embodiment of directed multi-deflected ion beam milling of a work piece, and, determining and controlling extent thereof, particularly showing the ion beam unit **100** in relation to the work piece imaging and milling detection unit **300** and the vacuum chamber assembly **210** of the vacuum unit, and all these in relation to the work piece and a surface thereof.

In general, Fig. 2 is completely sufficient for illustratively describing the method for directed multi-deflected ion beam milling of a work piece, of the present invention. However, for assuring understanding thereof, additional reference is made at this point to Figs. 3, 4, 5, 6, 8, 9, and 10, which may also be referred to for understanding
5 implementation of the numerous different exemplary specific preferred embodiments of the method for directed multi-deflected ion beam milling of a work piece, in accordance with the present invention.

Fig. 3 is a schematic diagram illustrating a side view of a more detailed version of the exemplary preferred embodiment illustrated in Fig. 2, particularly showing an
10 exemplary specific preferred embodiment of the device, being the ion beam unit **100**, including the ion beam directing and multi-deflecting assembly **120**, for *twice* deflecting an ion beam **10**, and showing an exemplary specific preferred embodiment of the work piece imaging and milling detection unit **300**.

Fig. 4 is a schematic diagram illustrating a side view of the directed multi-deflected
15 ion beam milling of a work piece, and, determining and controlling extent thereof, illustrated in Figs. 2 and 3, particularly showing a cross-sectional side view of a more detailed component level version of the device, being the ion beam unit **100**, including the ion beam directing and multi-deflecting assembly **120**, structured and functional for *twice* deflecting an ion beam **10**.

Fig. 5 is a schematic diagram illustrating a perspective view of the directed
20 multi-deflected ion beam milling of a work piece, illustrated in Figs. 2, 3, and 4, particularly showing an exemplary specific preferred embodiment of each of the ion beam first deflecting assembly **122** and the ion beam second deflecting assembly **124**, included in the ion beam directing and multi-deflecting assembly **120** of the ion beam unit **100**,
25 structured and functional for *twice* deflecting an ion beam **10**.

Figs. 6a - 6e are schematic diagrams together illustrating a perspective view of a rotational (angular) sequence of an ion beam directed and multi-deflected, relative to an arbitrarily assigned longitudinal axis **40** coaxial with the work piece, by the first ion beam deflecting assembly **122** and the second ion beam deflecting assembly **124a** and **124b**,
30 corresponding to a directed twice deflected ion beam type of directed multi-deflected ion beam **20** which rotates in a range of between 0° and 360° around the longitudinal axis **40**, and is directed towards, incident and impinges upon, and mills, a surface of the work piece.

Fig. 7a is a schematic diagram illustrating a perspective close-up view of a directed multi-deflected ion beam **20** (*twice* deflected) or **22** (*thrice* deflected) directed towards, incident and impinging upon, and milling, a surface of a first type of an exemplary work piece (a generally shaped rectangular slab), particularly showing relative geometries and dimensions of ion beam **20** or **22**, the surface, and the work piece.

Fig. 7b is a schematic diagram illustrating a perspective close-up view of a directed multi-deflected ion beam **20** (*twice* deflected) or **22** (*thrice* deflected) directed towards, incident and impinging upon, and milling, a surface of a second type of an exemplary work piece (a typical sample of a portion of a semiconductor wafer or chip wherein the surface (with a mask) is held by a sample holder element, for example, similar to that illustrated in Fig. 1), particularly showing relative geometries and dimensions of ion beam **20** or **22**, the surface, and the work piece.

Fig. 8 is a schematic diagram illustrating a side view of a more detailed version of the exemplary preferred embodiment illustrated in Fig. 2, particularly showing an exemplary specific preferred embodiment of the ion beam unit **100**, including the ion beam directing and multi-deflecting assembly **120**, for *thrice* deflecting an ion beam **10**, and an exemplary specific preferred embodiment of the work piece imaging and milling detection unit **300**.

Fig. 9 is a schematic diagram illustrating a side view of the directed multi-deflected ion beam milling of a work piece, and, determining and controlling extent thereof, illustrated in Figs. 2 and 8, particularly showing a cross-sectional side view of a more detailed component level version of the ion beam unit **100**, including the ion beam directing and multi-deflecting assembly **120**, structured and functional for *twice* deflecting an ion beam **10**.

Fig. 10 is a schematic diagram illustrating a perspective view of the directed multi-deflected ion beam milling of a work piece, illustrated in Figs. 2, 8, and 9, particularly showing an exemplary specific preferred embodiment of each of the ion beam first deflecting assembly **122**, the ion beam second deflecting assembly **124**, and the ion beam third deflecting assembly **140**, included in the ion beam directing and multi-deflecting assembly **120** of the ion beam unit **100**, structured and functional for *thrice* deflecting an ion beam.

Accordingly, with reference to Fig. 2, along with additional reference to Figs. 3, 4, 5, 6, 8, 9, and 10, the method for directed multi-deflected ion beam milling of a work piece

includes: providing an ion beam **10**; and directing and at least twice (for example, *twice* or *thrice*) deflecting provided ion beam **10**, for forming a directed multi-deflected ion beam **20a**, **20b**, or **20c**, wherein directed multi-deflected ion beam **20a**, **20b**, or **20c**, is directed towards, incident and impinges upon, and mills, a surface of the work piece.

5 In general, there are numerous different exemplary specific preferred embodiments of the method for directed multi-deflected ion beam milling of a work piece, in part, according to the specific spatial (directional, orientational, configurational) mode or manner, and according to the specific temporal (timing) mode or manner, of multi-deflecting and directing provided ion beam **10**, wherein directed multi-deflected ion
10 beam **20a**, **20b**, or **20c**, is directed towards, incident and impinges upon, and mills, a surface of the work piece. In particular, the specific spatial (directional, orientational, configurational) mode or manner of multi-deflecting and directing provided ion beam **10** is linear or rotational. In particular, the specific temporal (timing) mode or manner, of multi-deflecting and directing provided ion beam **10**, is continuous, discontinuous
15 (periodic, aperiodic, or pulsed), or a combination of continuous and discontinuous (periodic, aperiodic, or pulsed). Moreover, each specific spatial (directional, orientational, configurational) mode or manner, that is, linear or rotational, of multi-deflecting and directing provided ion beam **10**, can be implemented according to each specific temporal (timing) mode or manner, that is, continuous, discontinuous (periodic, aperiodic, or
20 pulsed), or a combination of continuous and discontinuous (periodic, aperiodic, or pulsed), of multi-deflecting and directing provided ion beam **10**.

More specifically, regarding the specific spatial (directional, orientational, configurational) mode or manner of multi-deflecting and directing provided ion beam **10**, there is multi-deflecting (for example, *twice* or *thrice* deflecting) and linearly or
25 rotationally directing provided ion beam **10**, for forming a respective linearly or rotationally directed multi-deflected (*twice* or *thrice* deflected, respectively) ion beam **20a**, **20b**, or **20c**, wherein the respective linearly or rotationally directed multi-deflected ion beam **20a**, **20b**, or **20c**, is respectively linearly or rotationally directed towards, incident and impinges upon, and mills, a surface of the work piece.

30 More specifically, regarding the specific temporal (timing) mode or manner, of multi-deflecting and directing provided ion beam **10**, there is multi-deflecting (for example, *twice* or *thrice* deflecting) and continuously, discontinuously, or, a combination of continuously and discontinuously, directing provided ion beam **10**, for forming a

respective continuously, discontinuously, or, a combination of continuously and discontinuously, directed multi-deflected (*twice* or *thrice* deflected, respectively) ion beam **20a**, **20b**, or **20c**, wherein the respective continuously, discontinuously, or, a combination of continuously and discontinuously, directed multi-deflected ion beam **20a**, **20b**, or **20c**, is
5 respectively continuously, discontinuously, or, a combination of continuously and discontinuously, directed towards, incident and impinges upon, and mills, a surface of the work piece.

Accordingly, regarding each specific temporal (timing) mode or manner, of multi-deflecting and directing provided ion beam **10**, implemented according to each
10 specific temporal (timing) mode or manner, of multi-deflecting and directing provided ion beam **10**, there is multi-deflecting (for example, *twice* or *thrice* deflecting) and continuously, discontinuously, or, a combination of continuously and discontinuously, linearly or rotationally directing provided ion beam **10**, for forming a respective continuously, discontinuously, or, a combination of continuously and discontinuously,
15 linearly or rotationally directed multi-deflected (*twice* or *thrice* deflected, respectively) ion beam **20a**, **20b**, or **20c**, wherein the respective continuously, discontinuously, or, a combination of continuously and discontinuously, linearly or rotationally directed multi-deflected ion beam **20a**, **20b**, or **20c**, is respectively continuously, discontinuously, or, a combination of continuously and discontinuously, linearly or rotationally directed
20 towards, incident and impinges upon, and mills, a surface of the work piece.

Each of the above described (spatially and temporally characterized) exemplary specific preferred embodiments of the method for directed multi-deflected ion beam milling of a work piece, according to a different specific spatial (directional, orientational, configurational) mode or manner, and according to a different specific temporal (timing)
25 mode or manner, of multi-deflecting (for example, *twice* or *thrice* deflecting) and directing provided ion beam **10**, is illustratively described in more detail hereinbelow. For this, as shown in Fig. 2, it is generally applicable to each exemplary specific preferred embodiment, that provided ion beam **10** is essentially coaxial with a longitudinal axis, herein, referred to as longitudinal axis **40**. Additionally, as shown in Fig. 2, it is generally
30 applicable to each exemplary specific preferred embodiment, that the work piece is essentially coaxial with longitudinal axis **40**. With reference to exemplary three-dimensional xyz coordinate axes system **50**, arbitrarily, longitudinal **40** extends in the direction of, along, and is coaxial with, the x-axis.

Linear Spatial Modes or Manners of Ion Beam Milling of a Work Piece

With reference to Fig. 2, provided ion beam **10** is linearly directed and extends in the direction of, and along, longitudinal axis **40** [i.e., the x-axis (in $z = 0$ domain)]. Then, linearly directed provided ion beam **10** is at least twice deflected (multi-deflected) and linearly directed, and is converted or transformed into, and becomes, linearly directed multi-deflected ion beam **20a**, **20b**, or **20c**, which is linearly directed and extends in the direction from above longitudinal axis **40** [i.e., the x-axis (in positive z-axis domain)], or from below longitudinal axis **40** [i.e., the x-axis (in negative z-axis domain)], or in the direction of, and along, longitudinal axis **40** [i.e., the x-axis (in $z = 0$ domain)], respectively, towards the work piece, followed by being incident and impinging upon, and milling, a surface of the work piece.

More specifically, the preceding description corresponds to three (linearly spatially characterized) main exemplary specific preferred embodiments of the method for directed multi-deflected ion beam milling of a work piece, each according to a different specific linear spatial (directional, orientational, configurational) mode or manner of multi-deflecting (for example, *twice* or *thrice* deflecting) and directing provided ion beam **10**, wherein linearly directed multi-deflected ion beam **20a**, **20b**, or **20c**, is linearly directed towards, incident and impinges upon, and mills, a surface of the work piece.

Moreover, each of these three (linearly spatially characterized) main exemplary specific preferred embodiments of the method for directed multi-deflected ion beam milling of a work piece, is implemented according to three main different specific temporal (timing) modes or manners of multi-deflecting (for example, *twice* or *thrice* deflecting) and linearly directing provided ion beam **10**, selected from the group consisting of a continuous type of temporal (timing) mode or manner of multi-deflecting and linearly directing provided ion beam **10**, a discontinuous (periodic, aperiodic, or pulsed) type of temporal (timing) mode or manner of multi-deflecting and linearly directing provided ion beam **10**, and, a combination of a continuous type and a discontinuous type of temporal (timing) mode or manner of multi-deflecting and linearly directing provided ion beam **10**, wherein linearly directed multi-deflected ion beam **20a**, **20b**, or **20c**, is linearly directed towards, incident and impinges upon, and mills, a surface of the work piece. Such exemplary specific preferred embodiments of the method for directed multi-deflected ion beam milling of a work piece, are illustratively described immediately following.

In the first main (linearly spatially characterized) exemplary specific preferred embodiment, provided ion beam **10** is at least twice deflected (multi-deflected) and then linearly directed, for forming a linearly directed multi-deflected ion beam **20a**, which is linearly directed and extends in the direction from above longitudinal axis **40** [i.e., the x-axis (in positive z-axis domain)], towards the work piece, followed by being incident and impinging upon, and milling, a surface of the work piece.

According to a continuous type of temporal (timing) mode or manner of multi-deflecting and linearly directing provided ion beam **10**, provided ion beam **10** is temporally continuously at least twice deflected (multi-deflected) and then temporally continuously linearly directed, for forming a temporally continuously linearly directed multi-deflected ion beam **20a**, which is temporally continuously linearly directed and extends in the direction from above longitudinal axis **40** [i.e., the x-axis (in positive z-axis domain)], towards the work piece, followed by being temporally continuously incident and impinging upon, and milling, a surface of the work piece.

According to a discontinuous type of temporal (timing) mode or manner of multi-deflecting and linearly directing provided ion beam **10**, provided ion beam **10** is temporally discontinuously (periodically or aperiodically) at least twice deflected (multi-deflected) and then temporally discontinuously (periodically or aperiodically) linearly directed, for forming a temporally discontinuously (periodically or aperiodically) linearly directed multi-deflected ion beam **20a**, which is temporally discontinuously (periodically or aperiodically) linearly directed and extends in the direction from above longitudinal axis **40** [i.e., the x-axis (in positive z-axis domain)], towards the work piece, followed by being temporally discontinuously (periodically or aperiodically) incident and impinging upon, and milling, a surface of the work piece.

According to a combination of a continuous type and a discontinuous type of temporal (timing) mode or manner of multi-deflecting and linearly directing provided ion beam **10**, provided ion beam **10** is temporally continuously and discontinuously (periodically or aperiodically) at least twice deflected (multi-deflected) and then temporally continuously and discontinuously (periodically or aperiodically) linearly directed, for forming a temporally continuously and discontinuously (periodically or aperiodically) linearly directed multi-deflected ion beam **20a**, which is temporally continuously and discontinuously (periodically or aperiodically) linearly directed and extends in the direction from above longitudinal axis **40** [i.e., the x-axis (in positive z-axis domain)], towards the

work piece, followed by being temporally continuously and discontinuously (periodically or aperiodically) incident and impinging upon, and milling, a surface of the work piece.

In the second main (linearly spatially characterized) exemplary specific preferred embodiment, provided ion beam **10** is at least twice deflected (multi-deflected) and then
5 linearly directed, for forming a linearly directed multi-deflected ion beam **20b**, which is linearly directed and extends in the direction from below longitudinal axis **40** [i.e., the x-axis (in negative z-axis domain)], towards the work piece, followed by being incident and impinging upon, and milling, a surface of the work piece.

According to a continuous type of temporal (timing) mode or manner of
10 multi-deflecting and directing provided ion beam **10**, provided ion beam **10** is temporally continuously at least twice deflected (multi-deflected) and then temporally continuously linearly directed, for forming a temporally continuously linearly directed multi-deflected ion beam **20b**, which is temporally continuously linearly directed and extends in the direction from below longitudinal axis **40** [i.e., the x-axis (in negative z-axis domain)],
15 towards the work piece, followed by being temporally continuously incident and impinging upon, and milling, a surface of the work piece.

According to a discontinuous type of temporal (timing) mode or manner of multi-deflecting and directing provided ion beam **10**, provided ion beam **10** is temporally discontinuously (periodically or aperiodically) at least twice deflected (multi-deflected)
20 and then temporally discontinuously (periodically or aperiodically) linearly directed, for forming a temporally discontinuously (periodically or aperiodically) linearly directed multi-deflected ion beam **20b**, which is temporally discontinuously (periodically or aperiodically) linearly directed and extends in the direction from below longitudinal axis **40** [i.e., the x-axis (in negative z-axis domain)], towards the work piece, followed by being
25 temporally discontinuously (periodically or aperiodically) incident and impinging upon, and milling, a surface of the work piece.

According to a combination of a continuous type and a discontinuous type of temporal (timing) mode or manner of multi-deflecting and directing provided ion beam **10**, provided ion beam **10** is temporally continuously and discontinuously (periodically or
30 aperiodically) at least twice deflected (multi-deflected) and then temporally continuously and discontinuously (periodically or aperiodically) linearly directed, for forming a temporally continuously and discontinuously (periodically or aperiodically) directed multi-deflected ion beam **20b**, which is temporally continuously and discontinuously

(periodically or aperiodically) linearly directed and extends in the direction from below longitudinal axis **40** [i.e., the x-axis (in negative z-axis domain)], towards the work piece, followed by being temporally continuously and discontinuously (periodically or aperiodically) incident and impinging upon, and milling, a surface of the work piece.

5 In the third main (linearly spatially characterized) exemplary specific preferred embodiment, provided ion beam **10** is at least twice deflected (multi-deflected) and then linearly directed, for forming a linearly directed multi-deflected ion beam **20c**, which is linearly directed and extends in the direction of, and along, longitudinal axis **40** [i.e., the x-axis (in $z = 0$ domain)], and therefore, work piece axis **40**, towards the work piece,
10 followed by being incident and impinging upon, and milling, a surface of the work piece.

 According to a continuous type of temporal (timing) mode or manner of multi-deflecting and linearly directing provided ion beam **10**, provided ion beam **10** is temporally continuously at least twice deflected (multi-deflected) and then temporally continuously linearly directed, for forming a temporally continuously linearly directed
15 multi-deflected ion beam **20c**, which is temporally continuously linearly directed and extends in the direction of, and along, longitudinal axis **40** [i.e., the x-axis (in $z = 0$ domain)], and therefore, work piece axis **40**, towards the work piece, followed by being temporally continuously incident and impinging upon, and milling, a surface of the work piece.

20 According to a discontinuous type of temporal (timing) mode or manner of multi-deflecting and linearly directing provided ion beam **10**, provided ion beam **10** is temporally discontinuously (periodically or aperiodically) at least twice deflected (multi-deflected) and then temporally discontinuously (periodically or aperiodically) linearly directed, for forming a temporally discontinuously (periodically or aperiodically)
25 linearly directed multi-deflected ion beam **20c**, which is temporally discontinuously (periodically or aperiodically) linearly directed and extends in the direction of, and along, longitudinal axis **40** [i.e., the x-axis (in $z = 0$ domain)], towards the work piece, followed by being temporally discontinuously (periodically or aperiodically) incident and impinging upon, and milling, a surface of the work piece.

30 According to a combination of a continuous type and a discontinuous type of temporal (timing) mode or manner of multi-deflecting and linearly directing provided ion beam **10**, provided ion beam **10** is temporally continuously and discontinuously (periodically or aperiodically) at least twice deflected (multi-deflected) and then temporally

continuously and discontinuously (periodically or aperiodically) linearly directed, for forming a temporally continuously and discontinuously (periodically or aperiodically) linearly directed multi-deflected ion beam **20c**, which is temporally continuously and discontinuously (periodically or aperiodically) linearly directed and extends in the direction of, and along, longitudinal axis **40** [i.e., the x-axis (in $z = 0$ domain)], towards the work piece, followed by being temporally continuously and discontinuously (periodically or aperiodically) incident and impinging upon, and milling, a surface of the work piece.

Rotational Spatial Modes or Manners of Ion Beam Milling of a Work Piece

With reference to Fig. 2, provided ion beam **10** is linearly directed and extends in the direction of, and along, longitudinal axis **40** [i.e., the x-axis (in $z = 0$ domain)]. Then, linearly directed provided ion beam **10** is at least twice deflected (multi-deflected) and rotationally directed, and is converted or transformed into, and becomes, rotationally directed multi-deflected ion beam **20a** or **20b**, or **20c**, which is rotationally directed and extends 'conically' or 'conically-like' (in Fig. 2, indicated by the large dashed line perspectively drawn circle **52**), or 'cylindrically' (in Fig. 2, indicated by the small dashed line perspectively drawn circle **54**), respectively, around longitudinal axis **40**, towards the work piece, followed by being incident and impinging upon, and milling, a surface of the work piece.

More specifically, the preceding description corresponds to two (rotationally spatially characterized) main exemplary specific preferred embodiments of the method for directed multi-deflected ion beam milling of a work piece, each according to a different specific rotational spatial (directional, orientational, configurational) mode or manner of multi-deflecting (for example, *twice* or *thrice* deflecting) and directing provided ion beam **10**, wherein rotationally directed multi-deflected ion beam **20a** or **20b**, or **20c**, is rotationally directed towards, incident and impinges upon, and mills, a surface of the work piece.

Moreover, each of these two (rotationally spatially characterized) main exemplary specific preferred embodiments of the method for directed multi-deflected ion beam milling of a work piece, is implemented according to three main different specific temporal (timing) modes or manners of multi-deflecting (for example, *twice* or *thrice* deflecting) and rotationally directing provided ion beam **10**, selected from the group consisting of a continuous type of temporal (timing) mode or manner of multi-deflecting and rotationally directing provided ion beam **10**, a discontinuous (periodic, aperiodic, or pulsed) type of

temporal (timing) mode or manner of multi-deflecting and rotationally directing provided ion beam **10**, and, a combination of a continuous type and a discontinuous type of temporal (timing) mode or manner of multi-deflecting and rotationally directing provided ion beam **10**, wherein rotationally directed multi-deflected ion beam **20a** or **20b**, or **20c**, is rotationally directed towards, incident and impinges upon, and mills, a surface of the work piece. Such exemplary specific preferred embodiments of the method for directed multi-deflected ion beam milling of a work piece, are illustratively described immediately following.

In the first main (rotationally spatially characterized) exemplary specific preferred embodiment, provided ion beam **10** is at least twice deflected (multi-deflected) and then rotationally directed, for forming a rotationally directed multi-deflected ion beam **20a** or **20b** which is rotationally directed and extends 'conically' or 'conically-like' around longitudinal axis **40**, towards the work piece, followed by being incident and impinging upon, and milling, a surface of the work piece.

According to a continuous type of temporal (timing) mode or manner of multi-deflecting and conically or conically-like rotationally directing provided ion beam **10**, provided ion beam **10** is temporally continuously at least twice deflected (multi-deflected) and then temporally continuously rotationally directed, for forming a temporally continuously rotationally directed multi-deflected ion beam **20a** or **20b**, which is temporally continuously rotationally directed and extends conically or conically-like around longitudinal axis **40**, towards the work piece, followed by being incident and impinging upon, and milling, a surface of the work piece.

According to a discontinuous type of temporal (timing) mode or manner of multi-deflecting and conically or conically-like rotationally directing provided ion beam **10**, provided ion beam **10** is temporally discontinuously (periodically or aperiodically) at least twice deflected (multi-deflected) and then temporally discontinuously (periodically or aperiodically) rotationally directed, for forming a temporally discontinuously (periodically or aperiodically) rotationally directed multi-deflected ion beam **20a** or **20b**, which is temporally discontinuously (periodically or aperiodically) rotationally directed and extends conically or conically-like around longitudinal axis **40**, towards the work piece, followed by being incident and impinging upon, and milling, a surface of the work piece.

According to a combination of a continuous type and a discontinuous type of temporal (timing) mode or manner of multi-deflecting and conically or conically-like

rotationally directing provided ion beam **10**, provided ion beam **10** is temporally continuously and discontinuously (periodically or aperiodically) at least twice deflected (multi-deflected) and then temporally continuously and discontinuously (periodically or aperiodically) rotationally directed, for forming a temporally continuously and discontinuously (periodically or aperiodically) rotationally directed multi-deflected ion beam **20a** or **20b**, which is temporally continuously and discontinuously (periodically or aperiodically) rotationally directed and extends conically or conically-like around longitudinal axis **40**, towards the work piece, followed by being incident and impinging upon, and milling, a surface of the work piece.

In the second main (rotationally spatially characterized) exemplary specific preferred embodiment, provided ion beam **10** is at least twice deflected (multi-deflected) and then rotationally directed, for forming a rotationally directed multi-deflected ion beam **20c** which is rotationally directed and extends 'cylindrically' around longitudinal axis **40**, towards the work piece, followed by being incident and impinging upon, and milling, a surface of the work piece, wherein provided ion beam **10** is coaxial with longitudinal axis **40**.

According to a continuous type of temporal (timing) mode or manner of multi-deflecting and cylindrically rotationally directing provided ion beam **10**, provided ion beam **10** is temporally continuously at least twice deflected (multi-deflected) and then temporally continuously rotationally directed, for forming a temporally continuously rotationally directed multi-deflected ion beam **20c**, which is temporally continuously rotationally directed and extends cylindrically around longitudinal axis **40**, towards the work piece, followed by being incident and impinging upon, and milling, a surface of the work piece.

According to a discontinuous type of temporal (timing) mode or manner of multi-deflecting and cylindrically rotationally directing provided ion beam **10**, provided ion beam **10** is temporally discontinuously (periodically or aperiodically) at least twice deflected (multi-deflected) and then temporally discontinuously (periodically or aperiodically) rotationally directed, for forming a temporally discontinuously (periodically or aperiodically) rotationally directed multi-deflected ion beam **20c**, which is temporally discontinuously (periodically or aperiodically) rotationally directed and extends cylindrically around longitudinal axis **40**, towards the work piece, followed by being incident and impinging upon, and milling, a surface of the work piece.

According to a combination of a continuous type and a discontinuous type of temporal (timing) mode or manner of multi-deflecting and cylindrically rotationally directing provided ion beam **10**, provided ion beam **10** is temporally continuously and discontinuously (periodically or aperiodically) at least twice deflected (multi-deflected) and then temporally continuously and discontinuously (periodically or aperiodically) rotationally directed, for forming a temporally continuously and discontinuously (periodically or aperiodically) rotationally directed multi-deflected ion beam **20c**, which is temporally continuously and discontinuously (periodically or aperiodically) rotationally directed and extends cylindrically around longitudinal axis **40**, towards the work piece, followed by being incident and impinging upon, and milling, a surface of the work piece.

With reference to Fig. 2, regarding the above illustratively described two (rotationally spatially characterized) main exemplary specific preferred embodiments, and three temporal (timing) modes of implementing each thereof, of the method for directed multi-deflected ion beam milling of a work piece, the conically or conically-like rotationally directed multi-deflected ion beam **20a** or **20b**, is according to a clockwise direction, a counter-clockwise direction, or a combination of a clockwise direction and a counter-clockwise direction, around longitudinal axis **40** (circle **52**).

Moreover, the clockwise direction, counter-clockwise direction, or combination of the clockwise direction and the counter-clockwise direction, of the conically or conically-like rotationally directed multi-deflected ion beam **20a** or **20b** around longitudinal axis **40** (circle **52**), is according to a partial rotation, that is, greater than 0° and less than 360° , or/and according to at least one complete rotation, that is, equal to or greater than 360° . Furthermore, such partial or/and complete rotation of the conically or conically-like rotationally directed multi-deflected ion beam **20a** or **20b** around longitudinal axis **40** (circle **52**) is according to a back-and-forth rocking type of conical or conical-like rotational motion, or/and according to a continuous or/and discontinuous (periodic, aperiodic, or pulsed) oscillatory type of conical or conical-like rotational motion.

Additionally, the conically or conically-like rotationally directed multi-deflected ion beam **20a** or **20b**, according to any of the just described clockwise direction, counter-clockwise direction, or combination of clockwise direction and counter-clockwise direction, rotational motions around longitudinal axis **40** (circle **52**), generally, projects as a circle or ellipse.

The cylindrically rotationally directed multi-deflected ion beam **20c**, is according to a clockwise direction, a counter-clockwise direction, or a combination of a clockwise direction and a counter-clockwise direction, around longitudinal axis **40** (circle **54**). Additionally, for the cylindrically rotationally directed multi-deflected ion beam **20c**, since longitudinal axis **40** is coaxial with provided ion beam **10**, the clockwise direction or a counter-clockwise direction of rotation of cylindrically rotationally directed multi-deflected ion beam **20c**, around longitudinal axis **40**, is equivalent to clockwise direction or a counter-clockwise direction of rotation of cylindrically rotationally directed multi-deflected ion beam **20c** around an axis of provided ion beam **10**, and therefore, around an axis of cylindrically rotationally directed multi-deflected ion beam **20c**.

Moreover, the clockwise direction, counter-clockwise direction, or combination of the clockwise direction and the counter-clockwise direction, of the cylindrically rotationally directed multi-deflected ion beam **20c** around longitudinal axis **40** (circle **54**), is according to a partial rotation, that is, greater than 0° and less than 360° , or/and according to at least one complete rotation, that is, equal to or greater than 360° . Furthermore, such partial or/and complete rotation of the cylindrically rotationally directed multi-deflected ion beam **20c** around longitudinal axis **40** (circle **54**) is according to a back-and-forth rocking type of cylindrical rotational motion, or/and according to a continuous or/and discontinuous (periodic, aperiodic, or pulsed) oscillatory type of cylindrical rotational motion. Additionally, the cylindrically rotationally directed multi-deflected ion beam **20c**, according to any of the just described clockwise direction, counter-clockwise direction, or combination of clockwise direction and counter-clockwise direction, cylindrical rotational motions around longitudinal axis **40** (circle **54**), generally, projects as a circle.

Main Parameters Characterizing the Directed Multi-deflected Ion Beam

With reference to Fig. 2, for the above illustratively described different exemplary specific preferred embodiments of the method for directed multi-deflected ion beam milling of a work piece, according to the specific linear or rotational spatial (directional, orientational, configurational) modes or manners, and according to the specific continuous or discontinuous temporal (timing) modes or manners, of multi-deflecting and directing provided ion beam **10**, wherein directed multi-deflected ion beam **20a**, **20b**, or **20c**, is directed towards, incident and impinges upon, and mills, a surface of the work piece, the following main parameters are applicable for characterizing directed multi-deflected ion

beam **20a**, **20b**, or **20c**, while directed towards, incident and impinging upon, and milling, a surface of the work piece.

Diameter or width of the ion beam: diameter or width of directed multi-deflected ion beam **20a**, **20b**, or **20c**, while being directed towards, incident and impinging upon, and
5 milling, a surface of the work piece. For a broad ion beam (BIB) type of ion beam milling of the work piece, the diameter or width of the ion beam is, preferably, in a range of between about 30 microns and about 2000 microns (2 millimeters), and more preferably, in a range of between about 200 microns and about 1000 microns (1 millimeter). For a
10 focused ion beam (FIB) type of ion beam milling of the work piece, the diameter or width of the ion beam is, preferably, in a range of between about 5 nanometers and about 100 nanometers.

Intensity (energy) of the ion beam: intensity (energy) of directed multi-deflected ion beam **20a**, **20b**, or **20c**, while being directed towards, incident and impinging upon, and
15 milling, a surface of the work piece. Preferably, in a range of between about 0.5 keV (kilo-electron volts) and about 12 keV (kilo-electron volts), and more preferably, in a range of between about 1 keV and about 10 keV.

First time derivative of the intensity (energy) of the ion beam: $d(\text{ion beam intensity or energy})/dt$, where t represents time. Rate of change of the intensity (energy) of directed multi-deflected ion beam **20a**, **20b**, or **20c**, with time, corresponding to the temporal rate of
20 change of the intensity (energy) of directed multi-deflected ion beam **20a**, **20b**, or **20c**, while being directed towards, incident and impinging upon, and milling, a surface of the work piece.

Second time derivative of the intensity (energy) of the ion beam: $d^2(\text{ion beam intensity or energy})/dt^2$, where t represents time. Rate of change of the first time derivative
25 of the intensity (energy) of directed multi-deflected ion beam **20a**, **20b**, or **20c**, corresponding to the temporal rate of change of the time derivative of the intensity (energy) of directed multi-deflected ion beam **20a**, **20b**, or **20c**, while being directed towards, incident and impinging upon, and milling, a surface of the work piece.

Current density or flux of the ion beam: two dimensional (area) density or flux of
30 the current of directed multi-deflected ion beam **20a**, **20b**, or **20c**, expressed in units of current per unit cross-sectional area of directed multi-deflected ion beam **20a**, **20b**, or **20c**, while being directed towards, incident and impinging upon, and milling, a surface of the work piece. Preferably, in a range of between about 0.08 mA/cm^2 (milli-ampere per square

centimeter) and about 500 mA/cm² (milli-ampere per square centimeter), and more preferably, in a range of between about 0.1 mA/cm² and about 30 mA/cm².

Rotational angle or angular displacement of the ion beam: the angle of rotation or angular displacement of rotationally directed multi-deflected ion beam **20a**, **20b**, or **20c**, around longitudinal axis **40**, while being directed towards, incident and impinging upon, and milling, a surface of the work piece. In a range of between 0 ° and 360 ° per rotation.

First time derivative of the rotational angle or angular displacement of the ion beam: $d(\text{rotational angle or angular displacement of the ion beam})/dt$, where t represents time. Rate of change of the rotational angle or angular displacement of rotationally directed multi-deflected ion beam **20a**, **20b**, or **20c**, around longitudinal axis **40**, while being directed towards, incident and impinging upon, and milling, a surface of the work piece, with time, corresponding to a temporal rate of change of the rotational angle or angular displacement of rotationally directed multi-deflected ion beam **20a**, **20b**, or **20c**, around longitudinal axis **40**, while directed towards, incident and impinging upon, and milling, a surface of the work piece.

Second time derivative of the rotational angle or angular displacement of the ion beam: $d^2(\text{rotational angle or angular displacement of the ion beam})/dt^2$, where t represents time. Rate of change of the first time derivative of the rotational angle or angular displacement of rotationally directed multi-deflected ion beam **20a**, **20b**, or **20c**, around longitudinal axis **40**, while being directed towards, incident and impinging upon, and milling, a surface of the work piece, with time, corresponding to a temporal rate of change of the first time derivative of the rotational angle or angular displacement of rotationally directed multi-deflected ion beam **20a**, **20b**, or **20c**, around longitudinal axis **40**, while directed towards, incident and impinging upon, and milling, a surface of the work piece.

Direction, path, or trajectory, of the ion beam: the direction, path, or trajectory, of directed multi-deflected ion beam **20a**, **20b**, or **20c**, corresponding to above illustratively described specific linear or (conical or conical-like, or cylindrical) rotational spatial (directional, orientational, configurational) modes or manners of multi-deflecting and directing provided ion beam **10**, relative to longitudinal axis **40**, while directed multi-deflected ion beam **20a**, **20b**, or **20c**, is directed towards, incident and impinging upon, and milling, a surface of the work piece.

Another main aspect of the present invention is a sub-combination of the method for directed multi-deflected ion beam milling of a work piece, as described hereinabove,

whereby there is provision of a method for directed multi-deflecting a provided ion beam, including the following main steps, and, components and functionalities thereof: directing and at least twice deflecting the provided ion beam, for forming a directed multi-deflected ion beam, by deflecting and directing the provided ion beam, for forming a directed once
5 deflected ion beam, and, deflecting and directing the directed once deflected ion beam, for forming a directed twice deflected ion beam being a type of the multi-deflected ion beam.

Accordingly, with reference to Fig. 2, along with additional reference to Figs. 3, 4, 5, 8, 9, and 10, the method for directed multi-deflecting a provided ion beam, includes: directing and at least twice deflecting the provided ion beam **10**, for forming a directed
10 multi-deflected ion beam **20a**, **20b**, or **20c**, by deflecting and directing the provided ion beam **10**, for forming a directed once deflected ion beam (for example, shown in Figs. 3 and 8 as **16a** or **16b**; and in Figs. 4, 5, 9, and 10, as **16**), and, deflecting and directing the directed once deflected ion beam (**16a** or **16b**, or **16**, respectively), for forming a directed twice deflected ion beam being a type of the directed multi-deflected ion beam **20a**, **20b**, or
15 **20c**.

Another main aspect of the present invention is provision of a device for directed multi-deflected ion beam milling of a work piece, including the following main components and functionalities thereof: an ion beam source assembly, for providing an ion beam; and an ion beam directing and multi-deflecting assembly, for directing and at least
20 twice deflecting the provided ion beam, for forming a directed multi-deflected ion beam, wherein the directed multi-deflected ion beam is directed towards, incident and impinges upon, and mills, a surface of the work piece.

Fig. 3 is a schematic diagram illustrating a side view of a more detailed version of the exemplary preferred embodiment illustrated in Fig. 2, particularly showing an
25 exemplary specific preferred embodiment of the device, being ion beam unit **100**, including ion beam directing and multi-deflecting assembly **120**, for *twice* deflecting an ion beam **10**, and showing an exemplary specific preferred embodiment of the work piece imaging and milling detection unit **300**.

Fig. 4 is a schematic diagram illustrating a side view of the directed multi-deflected
30 ion beam milling of a work piece, and, determining and controlling extent thereof, illustrated in Figs. 2 and 3, particularly showing a cross-sectional side view of a more detailed component level version of the device, being ion beam unit **100**, including ion

beam directing and multi-deflecting assembly **120**, structured and functional for *twice* deflecting an ion beam **10**.

The above illustrative description of the different exemplary specific preferred embodiments of the method for directed multi-deflected ion beam milling of a work piece, according to the specific linear or rotational spatial (directional, orientational, configurational) modes or manners, and according to the specific continuous or discontinuous temporal (timing) modes or manners, of multi-deflecting and directing provided ion beam **10**, wherein directed multi-deflected ion beam **20a**, **20b**, or **20c**, is directed towards, incident and impinges upon, and mills, a surface of the work piece, as shown in Fig. 2, is generally applicable for illustratively describing the device, being ion beam unit **100**, shown in Figs. 3 and 4, wherein ion beam unit **100** includes ion beam directing and multi-deflecting assembly **120**, specifically for *twice* deflecting provided ion beam **10**.

Accordingly, as shown in Figs. 2, 3, and 4, the device, being ion beam unit **100**, for directed multi-deflected ion beam milling of a work piece, includes the following main components and functionalities thereof: an ion beam source assembly **110**, for providing an ion beam **10**; and an ion beam directing and multi-deflecting assembly **120**, for directing and at least twice deflecting provided ion beam **10**, for forming directed multi-deflected ion beam **20a** or **20b** (in Figs. 2 and 3; and in Fig. 4, generally indicated as **20**) wherein directed multi-deflected ion beam **20a** or **20b** (in Figs. 2 and 3; **20** in Fig. 4) is directed towards, incident and impinges upon, and mills, a surface of the work piece.

As stated, ion beam source assembly **110** is for providing an ion beam **10**. In general, ion beam source assembly **110** generates ion beam **10** by ionizing a non-ionized particle supply, for example, which is supplied to ion beam source assembly **110**, for example, by a non-ionized particle supply assembly **112**. In general, non-ionized particle supply assembly **112** is either separate from, or integral to, ion beam source assembly **110**. Preferably, non-ionized particle supply assembly **112** is separate from, and operatively connected to, ion beam source assembly **110**, for example, as shown in Figs. 3 and 4.

In general, the non-ionized particle supply is essentially any type and phase of chemical which is capable of being ionized, such that in an ionized form is capable of milling the work piece. Preferably, the non-ionized particle supply is selected from the group consisting of a gas, and a liquid metal. An exemplary gas type of non-ionized

particle supply is an inert gas, such as argon, or xenon. An exemplary liquid metal type of non-ionized particle supply is liquid gallium.

The device, that is, ion beam unit **100**, of the present invention, is used for performing a broad ion beam (BIB) type of milling of the work piece, or, alternatively, for performing a focused ion beam (FIB) type of milling of the work piece. Accordingly, for a broad ion beam (BIB) type of implementation of the device, that is, ion beam unit **100**, of the present invention, the non-ionized particle supply is an inert gas, such as argon, or xenon. Alternatively, for a focused ion beam (FIB) milling type of implementation of the device, that is, ion beam unit **100**, of the present invention, the non-ionized particle supply is a liquid metal type of non-ionized particle supply, in particular, liquid gallium. Preferably, non-ionized particle supply **112** is an inert gas, such as argon, or xenon, for preventing or minimizing generation of artifacts on or within the surface of the work piece, thereby, improving the quality of the milled surface, during the ion beam milling of the work piece.

In general, in ion beam unit **100**, ion beam source assembly **110** can be of various different types. For example, ion beam source assembly **110** is a duoplasmatron (BIB) type of ion beam source assembly, or alternatively, is an electron impact (BIB) type of ion beam source assembly, wherein each, non-ionized particle supply **112** is an inert gas, such as argon, or xenon.

Fig. 5 is a schematic diagram illustrating a perspective view of the directed multi-deflected ion beam milling of a work piece, illustrated in Figs. 2, 3, and 4, particularly showing an exemplary specific preferred embodiment of each of the ion beam first deflecting assembly **122** and the ion beam second deflecting assembly **124**, included in ion beam directing and multi-deflecting assembly **120** of ion beam unit **100**, structured and functional for *twice* deflecting an ion beam **10**.

With reference to Figs. 2, 3, 4, and 5, ion beam directing and multi-deflecting assembly **120** is for directing and at least twice deflecting provided ion beam **10**, for forming directed multi-deflected ion beam **20a** or **20b** (in Figs. 2 and 3; **20** in Figs. 4 and 5), wherein directed multi-deflected ion beam **20a** or **20b** (in Figs. 2 and 3; **20** in Figs. 4 and 5) is directed towards, incident and impinges upon, and mills, a surface of the work piece.

Ion beam directing and multi-deflecting assembly **120** includes the following main components and functionalities thereof: an ion beam first deflecting assembly **122**, for

deflecting and directing provided ion beam **10**, for forming a directed once deflected ion beam **16a** or **16b** (in Fig. 3; **16** in Figs. 4 and 5) and an ion beam second deflecting assembly **124**, for deflecting and directing directed once deflected ion beam **16a** or **16b** (in Fig. 3; **16** in Figs. 4 and 5), for forming a directed twice deflected ion beam **20a** or **20b** (in Figs. 2 and 3; **20** in Figs. 4 and 5), respectively, being a type of directed multi-deflected ion beam **20a** or **20b** (in Figs. 2 and 3; **20** in Figs. 4 and 5), respectively.

In general, ion beam first deflecting assembly **122** includes a set of two pairs of, preferably, symmetrically positioned electrostatic plates or electrodes, wherein each pair, the electrostatic plates or electrodes are separated by a pre-determined separation distance.

For example, with reference to Figs. 4 and 5, ion beam first deflecting assembly **122** includes a set of two pairs, of, preferably, symmetrically positioned electrostatic plates or electrodes, that is, a first pair of symmetrically positioned electrostatic plates or electrodes **122a**, and a second pair of symmetrically positioned electrostatic plates or electrodes **122b**, wherein each pair, the electrostatic plates or electrodes are separated by a separation distance.

In ion beam first deflecting assembly **122**, each pair of electrostatic plates or electrodes, that is, first pair of electrostatic plates or electrodes **122a**, and second pair of electrostatic plates or electrodes **122b**, is supplied with a voltage provided by a designated operatively connected power supply, for example, **P₁** and **P₂**, respectively, as particularly shown in Fig. 4. During operation of ion beam first deflecting assembly **122**, the magnitude of the voltage supplied to first pair of electrostatic plates or electrodes **122a** by power supply **P₁**, and to second pair of electrostatic plates or electrodes **122b** by power supply **P₂**, determines the extent of spatial (linear and rotational) deflection of provided ion beam **10**, in general, and preferably, a directed focused ion beam **14**, relative to longitudinal axis **40**, for forming directed once deflected ion beam **16a** or **16b** (in Fig. 3; **16** in Figs. 4 and 5).

An important objective of operating ion beam first deflecting assembly **122**, is to optimally spatially (linearly or/and rotationally) and temporally (continuously or/and discontinuously) deflect and direct provided ion beam **10**, in general, and, preferably, directed focused ion beam **14**, into the inter-electrode space of ion beam second deflecting assembly **124**.

With reference to Fig. 4, ion beam first deflecting assembly **122** deflects provided ion beam **10**, in general, and preferably, directed focused ion beam **14**, relative to

longitudinal axis **40**, according to a deflection angle, or an angle of deflection, herein, referred to as θ_D . This is particularly shown in Fig. 4, where directed focused ion beam **14** enters, is deflected according to a deflection angle, θ_D , and exits, ion beam first deflecting assembly **122** in the form of a directed once deflected ion beam **16**.

5 In general, ion beam second deflecting assembly **124** includes a set of two (an inner and an outer) symmetrically and concentrically positioned and spherically or elliptically shaped or configured electrostatic plates or electrodes, wherein the electrostatic plates or electrodes are uniformly (i.e., circumferentially) separated by a pre-determined separation distance. For example, with reference to Figs. 4 and 5, ion beam second deflecting
10 assembly **124** includes a set of two symmetrically and concentrically positioned and spherically or elliptically shaped or configured electrostatic plates or electrodes, that is, a inner symmetrically positioned and spherically or elliptically shaped or configured electrostatic plate or electrodes **124a**, and an outer symmetrically positioned and spherically or elliptically shaped or configured electrostatic plate or electrode **124b**,
15 wherein the electrostatic plates or electrodes are separated by a separation distance.

In ion beam second deflecting assembly **124**, each electrostatic plate or electrode, that is, inner electrostatic plate or electrode **124a**, and outer electrostatic plate or electrode **124b**, is supplied with a voltage provided by a designated operatively connected power supply, for example, **P₃** and **P₄**, respectively, as particularly shown in Fig. 4. During
20 operation of ion beam second deflecting assembly **124**, the magnitude of the voltage supplied to inner electrostatic plate or electrode **124a** by power supply **P₃**, and to outer electrostatic plate or electrode **124b** by power supply **P₄**, determines the extent of spatial (linear and rotational) deflection of directed once deflected ion beam **16a** or **16b** (in Fig. 3; **16** in Figs. 4 and 5), relative to longitudinal axis **40**, for forming directed twice deflected
25 ion beam **20a** or **20b** (in Figs. 2 and 3; **20** in Figs. 4 and 5), respectively, being a type of directed multi-deflected ion beam **20a** or **20b** (in Figs. 2 and 3; **20** in Figs. 4 and 5), respectively.

An important objective of operating ion beam second deflecting assembly **124**, is to optimally spatially (linearly or/and rotationally) and temporally (continuously or/and
30 discontinuously) deflect and direct directed once deflected ion beam **16a** or **16b** (in Fig. 3; **16** in Figs. 4 and 5), in the form of directed twice deflected ion beam **20a** or **20b** (in Figs. 2 and 3; **20** in Figs. 4 and 5), respectively, being multi-deflected ion beam **20a** or **20b**, respectively, such that directed twice deflected ion beam **20a** or **20b**, being directed

multi-deflected ion beam **20a** or **20b**, is directed towards, incident and impinges upon, and mills, a surface of the work piece.

With reference to Fig. 4, ion beam second deflecting assembly **124** deflects directed once deflected ion beam **16**, relative to longitudinal axis **40**, according to an incidence angle, or an angle of incidence, herein, referred to as θ_i , upon a surface of the work piece, wherein directed twice deflected ion beam **20a** or **20b**, being directed multi-deflected ion beam **20a** or **20b**, respectively, is directed towards, incident and impinges upon, and mills, the surface of the work piece. The maximum incidence angle or angle of incidence, θ_i , of directed twice deflected ion beam **20a** or **20b**, being directed multi-deflected ion beam **20a** or **20b**, respectively, relative to longitudinal axis **40** and upon a surface of the work piece is, preferably, in a range of between about 0° and about 90° , and more preferably, between about 0° and about 30° .

As shown in Fig. 4, $\alpha_D: (90 - \theta_D)$ corresponds to the half-angle at the apex of inner electrostatic plate or electrode **124a** of ion beam second deflecting assembly **124**, while $\alpha_i: (90 - \theta_i)$ corresponds to the half-angle at the apex of second electrostatic plate or electrode **124b** of ion beam second deflecting assembly **124**, which faces the work piece.

With reference to Figs. 3 and 4, in ion beam unit **100**, ion beam directing and multi-deflecting assembly **120**, preferably, further includes an ion beam focusing assembly **126**, for focusing and directing provided ion beam **10**, for forming a directed focused ion beam **14**. With reference to Fig. 4, ion beam focusing assembly **126** includes the main components: a first electrostatic lens **132**, a second electrostatic lens **134**, and an aperture **136**.

First electrostatic lens **132** is for preliminary focusing of ion beam **10** provided by ion beam source assembly **110**. First electrostatic lens **132** is supplied with a voltage provided by a designated operatively connected power supply, for example, **P₅**, as particularly shown in Fig. 4.

Second electrostatic lens **134** is for further focusing, and directing, of ion beam **10** provided by ion beam source assembly **110**, to the inter-electrode space between first pair of electrostatic plates or electrodes **122a** and second pair of electrostatic plates or electrodes **122b** of ion beam first deflecting assembly **122**. Second electrostatic lens **134** is supplied with a voltage provided by a designated operatively connected power supply, for example, **P₆**, as particularly shown in Fig. 4.

Aperture **136** is for limiting or restricting the diameter of ion beam **10** provided by ion beam source assembly **110**.

With reference to Figs. 3 and 4, in ion beam directing and multi-deflecting assembly **120** of ion beam unit **100**, ion beam focusing assembly **126**, optionally, and preferably, is operatively connected to, or further includes an ion beam deflecting sub-assembly **128**, for deflecting provided ion beam **10** in the direction of, and along longitudinal axis **40** [i.e., the x-axis (in $z = 0$ domain)], such that provided ion beam **10** is maintained coaxial with longitudinal axis **40** to a high degree of accuracy.

With reference to Figs. 3 and 4, in ion beam unit **100**, ion beam directing and multi-deflecting assembly **120**, preferably, further includes an ion beam extractor assembly **130**, for extracting and directing ion beam **10** provided by ion beam source assembly **110**, for forming a directed extracted ion beam **12**.

With reference to Figs. 3 and 4, in ion beam unit **100**, ion beam directing and multi-deflecting assembly **120**, preferably, further includes an ion beam vacuum chamber assembly **150**, for housing the various assemblies, sub-assemblies, components, and elements, of ion beam directing and multi-deflecting assembly **120**., and for allowing maintenance of a vacuum environment of ion beam unit **100** when operatively connected to vacuum chamber assembly **210** of a vacuum unit, in particular, vacuum unit **200** of system **70**, as further described hereinbelow, with reference to Fig. 11, 12, and 13.

Fig. 5 is a schematic diagram illustrating a perspective view of the directed multi-deflected ion beam milling of a work piece, illustrated in Figs. 2, 3, and 4, particularly showing an exemplary specific preferred embodiment of each of the ion beam first deflecting assembly **122** and the ion beam second deflecting assembly **124**, included in ion beam directing and multi-deflecting assembly **120** of ion beam unit **100**, structured and functional for *twice* deflecting an ion beam **10**.

Figs. 6a - 6e are schematic diagrams together illustrating a perspective view of a rotational (angular) sequence of an ion beam directed and multi-deflected, relative to arbitrarily assigned longitudinal axis **40** coaxial with the work piece, by first ion beam deflecting assembly **122** and second ion beam deflecting assembly **124a** and **124b**, corresponding to a directed twice deflected ion beam type of directed multi-deflected ion beam **20** which rotates in a range of between 0° and 360° around longitudinal axis **40**, and is directed towards, incident and impinges upon, and mills, a surface of the work piece.

Fig. 7a is a schematic diagram illustrating a perspective close-up view of a directed multi-deflected ion beam **20** (*twice* deflected) or **22** (*thrice* deflected) directed towards, incident and impinging upon, and milling, a surface of a first type of an exemplary work piece (a generally shaped rectangular slab), particularly showing relative geometries and dimensions of ion beam **20** or **22**, the surface, and the work piece. Fig. 7b is a schematic diagram illustrating a perspective close-up view of a directed multi-deflected ion beam **20** (*twice* deflected) or **22** (*thrice* deflected) directed towards, incident and impinging upon, and milling, a surface of a second type of an exemplary work piece (a typical sample of a portion of a semiconductor wafer or chip wherein the surface (with a mask) is held by a sample holder element, for example, similar to that illustrated in Fig. 1), particularly showing relative geometries and dimensions of ion beam **20** or **22**, the surface, and the work piece. The diameter, *d*, of the directed multi-deflected ion beam **20** (*twice* deflected) or **22** (*thrice* deflected), is preferably, in a range of between about 30 microns and about 2000 microns (2 millimeters), and more preferably, in a range of between about 200 microns and about 1000 microns (1 millimeter).

Fig. 8 is a schematic diagram illustrating a side view of a more detailed version of the exemplary preferred embodiment illustrated in Fig. 2, particularly showing an exemplary specific preferred embodiment of the ion beam unit **100**, including the ion beam directing and multi-deflecting assembly **120**, for *thrice* deflecting an ion beam **10**, and an exemplary specific preferred embodiment of the work piece imaging and milling detection unit **300**.

The above illustrative description of the different exemplary specific preferred embodiments of the method for directed multi-deflected ion beam milling of a work piece, according to the specific linear or rotational spatial (directional, orientational, configurational) modes or manners, and according to the specific continuous or discontinuous temporal (timing) modes or manners, of multi-deflecting and directing provided ion beam **10**, wherein directed multi-deflected ion beam **20a**, **20b**, or **20c**, is directed towards, incident and impinges upon, and mills, a surface of the work piece, as shown in Fig. 2, is generally applicable for illustratively describing the device, being ion beam unit **100**, shown in Fig. 8, wherein ion beam unit **100** includes ion beam directing and multi-deflecting assembly **120**, specifically for *thrice* deflecting provided ion beam **10**.

Fig. 9 is a schematic diagram illustrating a side view of the directed multi-deflected ion beam milling of a work piece, and, determining and controlling extent thereof,

illustrated in Figs. 2 and 8, particularly showing a cross-sectional side view of a more detailed component level version of the ion beam unit **100**, including the ion beam directing and multi-deflecting assembly **120**, structured and functional for *twice* deflecting an ion beam **10**.

5 Fig. 10 is a schematic diagram illustrating a perspective view of the directed multi-deflected ion beam milling of a work piece, illustrated in Figs. 2, 8, and 9, particularly showing an exemplary specific preferred embodiment of each of the ion beam first deflecting assembly **122**, the ion beam second deflecting assembly **124**, and the ion beam third deflecting assembly **140**, included in the ion beam directing and
10 multi-deflecting assembly **120** of the ion beam unit **100**, structured and functional for *thrice* deflecting an ion beam.

Another main aspect of the present invention is a sub-combination of the device for directed multi-deflected ion beam milling of a work piece, whereby there is provision of a device for directed multi-deflecting a provided ion beam, including the following main
15 components and functionalities thereof: an ion beam directing and multi-deflecting assembly, for directing and at least twice deflecting the provided ion beam, for forming a directed multi-deflected ion beam, wherein the ion beam directing and multi-deflecting assembly includes an ion beam first deflecting assembly, for deflecting and directing the provided ion beam, for forming a directed once deflected ion beam, and an ion beam
20 second deflecting assembly, for deflecting and directing the directed once deflected ion beam, for forming a directed twice deflected ion beam being a type of the multi-deflected ion beam.

Another main aspect of the present invention is provision of a system for directed multi-deflected ion beam milling of a work piece, including the following main
25 components: an ion beam unit, wherein the ion beam unit includes an ion beam source assembly, for providing an ion beam, and an ion beam directing and multi-deflecting assembly, for directing and at least twice deflecting the provided ion beam, for forming a directed multi-deflected ion beam, wherein the directed multi-deflected ion beam is directed towards, incident and impinges upon, and mills, a surface of the work piece; and a
30 vacuum unit, operatively connected to the ion beam unit, for providing and maintaining a vacuum environment for the ion beam unit and the work piece.

Preferably, the vacuum unit includes the work piece. More specifically, preferably, the work piece is included inside the vacuum chamber assembly of the vacuum unit, in a

stationary (static or fixed) configuration, or in a movable configuration, as well as in a removable configuration, relative to the directed multi-deflected ion beam, and relative to the vacuum chamber assembly of the vacuum unit, for example, by operative connection of the work piece to a work piece manipulating and positioning unit.

5 Preferably, the system further includes electronics and process control utilities, operatively connected to the ion beam unit and to the vacuum unit, for providing electronics to, and enabling process control of, the ion beam unit and the vacuum unit. Optionally, and preferably, the system further includes at least one additional unit selected from the group consisting of: a work piece imaging and milling detection unit, a work
10 piece manipulating and positioning unit, an anti-vibration unit, a component imaging unit, and a work piece analytical unit, wherein each additional unit is operatively connected to the vacuum unit. Preferably, the electronics and process control utilities is also operatively connected to each additional unit, for providing electronics to, and enabling process control of, each additional unit, in a manner operatively integrated with the ion beam unit and the
15 vacuum unit.

Fig. 11 is a block diagram illustrating an exemplary preferred embodiment of the system, herein, generally referred to as system **70**, for directed multi-deflected ion beam milling of a work piece, including the main components: ion beam unit **100**, as previously illustratively described hereinabove, and a vacuum unit **200**. Preferably, vacuum unit **200**
20 includes the work piece. Fig. 12 is an (isometric) schematic diagram illustrating a perspective view of system **70**, and additional units thereof, for directed multi-deflected ion beam milling of a work piece, illustrated in Fig. 11. Fig. 13 is an (isometric) schematic diagram illustrating a top view of system **70** illustrated in Figs. 11 and 12.

In system **70** shown in Figs. 11, 12, and 13, ion beam unit **100**, as previously
25 illustratively described hereinabove, with reference to Figs. 2 - 10, includes ion beam source assembly **110**, for providing ion beam **10**, and ion beam directing and multi-deflecting assembly **120**, for directing and at least twice deflecting provided ion beam **10**, for forming a directed multi-deflected ion beam **20**, wherein directed multi-deflected ion beam **20** is directed towards, incident and impinges upon, and mills, a
30 surface of the work piece. Vacuum unit **200** is operatively connected to ion beam unit **100** for providing and maintaining a vacuum environment for ion beam unit **100** and the work piece. Preferably, as shown in Figs. 11, 12, and 13, system **70** further includes electronics and process control utilities **800**, operatively connected (for example, in Fig. 11, indicated

by the larger ellipse intersecting operative connection of ion beam unit **100** and vacuum unit **200**) to ion beam unit **100** and to vacuum unit **200**, for providing electronics to, and enabling process control of, ion beam unit **100** and vacuum unit **200**.

Optionally, and preferably, system **70** further includes at least one additional unit
5 selected from the group consisting of: a work piece imaging and milling detection unit **300**,
a work piece manipulating and positioning unit **400**, an anti-vibration unit **500**, a
component imaging unit **600**, and at least one work piece analytical unit **700**, wherein each
additional unit is operatively connected to vacuum unit **200**. Preferably, electronics and
process control utilities **800** is also operatively connected to each additional unit, for
10 providing electronics to, and enabling process control of, each additional unit, in a manner
operatively integrated with ion beam unit **100** and vacuum unit **200**.

Accordingly, the present invention provides various alternative specific exemplary
preferred embodiments of the system, that is, system **70**, for directed multi-deflected ion
beam milling of a work piece.

15 In a non-limiting manner, as shown in Figs. 12 and 13, several units or components
thereof, of system **70** are directly mounted onto, and operatively connected to, a fixed or
mobile table, stand, or frame, type of system support assembly **900**, including appropriately
constructed support elements, legs, brackets, and mobile elements, such as wheels, whereas
other system units or components thereof are mounted onto those system units or
20 components thereof which are directly mounted onto system support assembly **900**.

As stated, with reference to Figs. 11, 12, and 13, in system **70**, vacuum unit **200**,
preferably including the work piece, is operatively connected to ion beam unit **100** for
providing and maintaining a vacuum environment for ion beam unit **100** and the work
piece. Vacuum unit **200** also functions as an overall structure or housing of ion beam unit
25 **100** and of the work piece, as well as of optional additional units of system **70**.

With respect to functionality and operation of vacuum unit **200**, vacuum unit **200**
includes the following main components: a vacuum chamber assembly **210**, a work piece
inserting/removing assembly **220**, a vacuum gauge assembly, a pre-pump assembly, a high
vacuum pump assembly, and a vacuum distribution assembly.

30 Vacuum chamber assembly **210**, as particularly shown in Figs. 2, 3, 4, 8, and 9, in
relation to ion beam unit **100** and work piece imaging and milling detection unit **300**, and
in Fig. 12, in relation to various system units, functions as the structure which provides the
vacuum environment for ion beam unit **100**, and components thereof, and the various

possible optional additional units, and components thereof, of system 70. Vacuum chamber assembly 210 also functions as an overall structure or housing of ion beam unit 100, and components thereof, and the various possible optional additional units, and components thereof, of system 70. For example, preferably, the work piece is included
5 inside vacuum chamber 210 assembly of vacuum unit 200, in a stationary (static or fixed) configuration, or in a movable configuration, as well as in a removable configuration, relative to directed multi-deflected ion beam 20, and relative to vacuum chamber assembly 210 of vacuum unit 200, for example, by operative connection of the work piece to work piece manipulating and positioning unit 400.

10 Vacuum chamber assembly 210 is the location of the overall vacuum environment of system 70. Vacuum chamber assembly 210 is operatively connected to ion beam unit 100, and to each optional additional unit of system 70, for example, work piece imaging and milling detection unit 300, work piece manipulating and positioning unit 400, anti-vibration unit 500, component imaging unit 600, and at least one work piece analytical unit
15 700. Vacuum chamber assembly 210 houses work piece inserting/removing assembly 220, and the vacuum gauge assembly. The other assemblies, that is, vacuum gauge assembly, pre-pump assembly, high vacuum pump assembly, and vacuum distribution assembly, of vacuum unit 200, are located at various different positions throughout system 70, and are operatively connected to vacuum chamber assembly 210.

20 Work piece inserting/removing assembly 220 (for example, partly shown in Fig. 12) functions for enabling inserting of the work piece into vacuum chamber assembly 210, and enabling removing of the work piece from vacuum chamber assembly 210, for example, via work piece manipulating and positioning unit 400 (Fig. 15). A first specific exemplary embodiment of work piece inserting/removing assembly 220 is in the form of a
25 sealed shutter or shutter-like element, which operates during the time of inserting the work piece into vacuum chamber assembly 210, or removing the work piece from vacuum chamber assembly 210. A second specific exemplary embodiment of work piece inserting/removing assembly 220 is in the form of an air lock.

For an exemplary preferred embodiment of system 70 which includes work piece
30 manipulating and positioning unit 400, then, work piece inserting/removing assembly 220, for example, in the form of an air lock, functions for preserving the vacuum environment existing throughout vacuum chamber assembly 210 of vacuum unit 200, at the time of inserting the work piece into vacuum chamber assembly 210, or removing the work piece

from vacuum chamber assembly **210**, via work piece manipulating and positioning unit **400**. Such a work piece inserting/removing assembly **220** typically includes as main components: a chamber, and a connecting valve.

With reference to Fig. 15, in such an embodiment, the chamber functions as the region or volume of space within which takes place loading the work piece onto a work piece holder assembly **420**, or unloading the work piece from work piece holder assembly **420**. The internal environment of the chamber is either at atmospheric pressure, or at vacuum, depending upon the actual stage of loading of the work piece onto work piece holder assembly **420**, or of unloading of the work piece from work piece holder assembly **420**. For an exemplary preferred embodiment of system **70** which includes work piece manipulating and positioning unit **400**, then, for example, 5-axis / 6 DOF (degree-of-freedom) work piece manipulating and positioning assembly **410** of work piece manipulating and positioning unit **400** is used for transferring of work piece holder assembly **420** between the chamber of the air lock assembly and vacuum chamber assembly **210** of vacuum unit **200**.

Further, in such an embodiment, the connecting valve functions for joining the region or volume of space of the chamber of the air lock assembly to the region or volume of space of vacuum chamber assembly **210**, as well as for separating the region or volume of space of the chamber of the air lock assembly from the region or volume of space of vacuum chamber assembly **210**. In general, the connecting valve is essentially any type of valve which functions and is structured for enabling manual, semi-automatic, or fully automatic, joining of a region or volume of space of a first chamber to a region or volume of space of a second chamber, as well as for separating the region or volume of space of the first chamber from the region or volume of space of the second chamber. Preferably, the connecting valve functions and is structured for enabling fully automatic operation during the joining or separating of the regions or volumes of spaces of the chamber of the air lock assembly and vacuum chamber assembly **210**. Such an automatic connecting valve is either a pneumatic or electrical type of valve. Alternatively, the connecting valve functions and is structured for enabling manual operation during the joining or separating of the regions or volumes of spaces of the chamber of the air lock assembly and vacuum chamber assembly **210**. An exemplary type of manual connecting valve is a type of valve which is opened or closed via a manual handle.

For an exemplary preferred embodiment of system 70 which does not include sample manipulating and positioning unit 400, then work piece inserting/removing assembly 220 in the form of an air lock, preferably, further includes a work piece holder receiver.

- 5 The vacuum gauge assembly functions for continuously gauging or monitoring the vacuum state existing within vacuum chamber assembly 210, and the vacuum state existing within the chamber of the air lock assembly, at any time before, during, or after, loading of the work piece onto work piece holder assembly 420, or unloading of the work piece from work piece holder assembly 420, via work piece manipulating and positioning unit 400.
- 10 The vacuum gauge assembly includes as main components: at least one vacuum gauge operatively connected to vacuum chamber assembly 210, and at least one vacuum gauge operatively connected to the chamber of the air lock assembly.

 In vacuum unit 200, the pre-pump assembly, and the high vacuum pump assembly are for pumping vacuum chamber assembly 210 down to about 10^{-3} Torr, and down to
15 about 10^{-6} Torr, respectively. Vacuum unit 200 optionally includes assemblies and related equipment for providing and maintaining ultra-high vacuum conditions, for example, with a vacuum environment having a pressure as low as about 10^{-10} Torr, in vacuum chamber assembly 210, and in optional additional units of system 70.

 The vacuum distribution assembly is for distributing and maintaining different pre-
20 determined levels of vacuum to different units of system 70, which are operatively connected to vacuum chamber assembly 210 of vacuum unit 200, and for purging the different units of system 70 of positive pressure. For example, purging the air lock assembly of vacuum unit 200 at any time before, during, or after, loading of the work piece onto work piece holder assembly 420, or unloading of the work piece from work piece
25 holder assembly 420, via work piece manipulating and positioning unit 400.

 With reference to Figs. 11, 12, 13, and 14, system 70, optionally, and preferably, includes work piece imaging and milling detection unit 300, for imaging the work piece, and determining and controlling the extent of ion beam milling of the work piece. Preferably, work piece imaging and milling detection unit 300 is operatively connected to
30 vacuum chamber assembly 210 of vacuum unit 200.

 Fig. 14 is an (isometric) schematic diagram illustrating a perspective view of an exemplary specific preferred embodiment of the work piece imaging and milling detection unit 300, and main components thereof, in relation to the ion beam unit 100, the work piece

manipulating and positioning unit **400**, the component imaging unit **600**, and all these in relation to the work piece, as part of system **70** illustrated in Figs. 12 and 13.

With reference to Fig. 14, work piece imaging and milling detection unit **300** includes the main components of: a scanning electron microscope (SEM) column assembly **310**, a secondary electron detector assembly **320**, a back-scattered electron detector assembly **330**, and a transmission electron detector assembly **340**. Work piece imaging and milling detection unit **300**, and selected main components thereof, are shown in Figs. 2, 3, 4, 8, 9, 16, and 17, in operative relation to the various system units, and assemblies thereof, illustrated therein.

SEM column assembly **310** is for generating an electron beam probe of primary electrons, herein, referenced by **302** (in Figs. 2, 3, 4, 8, 9, 17a, and 17b), and by PE (in Figs. 16, 17a, and 17b), which scan along a surface of the work piece.

In system **70**, wherein optionally, and preferably, there is included work piece imaging and milling detection unit **300**, then SEM column assembly **310** included therein, together with secondary electron detector assembly **320**, or/and back-scattered electron detector assembly **330**, can also function for physically analyzing the surface of the work piece. Alternatively, or additionally, SEM column assembly **310** can operate in STEM mode by utilizing transmitted electron detector assembly **340** of work piece imaging and milling detection unit **300**, for the work piece being transparent to electrons, for physically analyzing the bulk material of the work piece.

Secondary electron detector assembly **320** is for detecting secondary electrons, herein, referenced by **318** (Figs. 3 and 8), and by SE (Fig. 16), which are emitted from a surface of the work piece, as a result of interaction between primary electrons **302** (Figs. 2, 3, 4, 8, 9, 17a, and 17b), and PE (Figs. 16, 17a, and 17b), and the surface of the work piece.

A signal of detected secondary electrons **318** is processed for obtaining images of the surface of the work piece. Preferably, secondary electron detector assembly **320** is continuously operative during implementation of the present invention.

Back-scattered electron detector assembly **330** is for detecting primary electrons **302** (Figs. 2, 3, 4, 8, 9, 17a, and 17b), and PE (Figs. 16, 17a, and 17b), which are back-scattered from the sub-surface or/and surface layers of the work piece. A signal of the detected back-scattered primary electrons **308** (Figs. 3 and 8) is processed for obtaining images of the surface of the work piece. Preferably, back-scattered electron detector assembly **330** is continuously operative during implementation of the present invention.

Transmission electron detector assembly **340** is for detecting primary electrons **302** (Figs. 2, 3, 4, 8, 9, 17a, and 17b), and PE (Figs. 16, 17a, and 17b), which are transmitted through the work piece. Preferably, transmission electron detector assembly **340** is continuously operative during implementation of the present invention.

5 For brevity, in Fig. 2, secondary electrons and back-scattered electrons, herein, collectively referred to by **304**, are generally shown being detected by work piece imaging and milling detection unit **300**.

With reference to Figs. 11, 12, 13, and 15, system **70**, optionally, and preferably, includes work piece manipulating and positioning unit **400**, for manipulating the work
10 piece. Work piece manipulating and positioning unit **400** is operatively connected to vacuum chamber assembly **210** of vacuum unit **200**.

Fig. 15 is an (isometric) schematic diagram illustrating a perspective view of an exemplary specific preferred embodiment of the work piece manipulating and positioning unit **400**, and main components thereof, particularly showing close-up views of the work
15 piece holder assembly **420** without a work piece (a), and with a work piece (b), as part of system **70** illustrated in Figs. 11, 12, and 13. As shown in Fig. 15, work piece manipulating and positioning unit **400**, includes the main components of: a 5-axis / 6 DOF (degrees of freedom) work piece manipulator assembly **410**, a work piece holder assembly **420**, and a calibrating assembly **430**.

20 5-axis / 6 DOF (degrees of freedom) work piece manipulator assembly **410** is for manipulating and positioning the work piece relative to the directed multi-deflected ion beam **20**, and relative to vacuum chamber assembly **210** of vacuum unit **200**.

Work piece holder assembly **420** is for facilitating inserting of the work piece into vacuum chamber assembly **210**, and facilitating removing of the work piece from vacuum
25 chamber assembly **210**, of vacuum unit **200**. Work piece holder assembly **420** additionally functions for holding the work piece during the directed multi-deflected ion beam milling of the work piece.

Calibrating assembly **430** is for enabling calibration of the work piece with respect to directed multi-deflected ion beam **20** of ion beam unit **100**, and with respect to the beam
30 of primary electrons transmitted by SEM column assembly **310** of work piece imaging and milling detection unit **300**.

For an exemplary preferred embodiment of system **70** which includes work piece manipulating and positioning unit **400**, then, for example, 5-axis / 6 DOF

(degree-of-freedom) work piece manipulating and positioning assembly **410** of work piece manipulating and positioning unit **400** is used for transferring of work piece holder assembly **420** between the chamber of the air lock assembly and vacuum chamber assembly **210** of vacuum unit **200**.

5 With reference to Figs. 11, 12, and 13, system **70**, optionally, and preferably, includes anti-vibration unit **500**, for preventing or minimizing occurrence of vibrations during operation of system **70**. Anti-vibration unit **500**, and components thereof, are directly mounted onto, and operatively connected to, system support assembly **900**. Anti-vibration unit **500** includes the main components of a plurality of electro-pneumatic
10 or/and electro-mechanical active damping assemblies, for example, four electro-pneumatic active damping assemblies, generally indicated by **500** in Fig. 13. Preferably, electronics and process control utilities **800** is operatively connected to anti-vibration unit **500**, for providing electronics to, and enabling process control of anti-vibration unit **500**.

 With reference to Figs. 11, 12, 13, and 14, system **70**, optionally, and preferably,
15 includes component imaging unit **600**, for imaging the work piece, as well as components of selected optional and preferred additional units, in particular, work piece imaging and milling detection unit **300**, work piece manipulating and positioning unit **400**, and at least one work piece analytical unit **700**. Component imaging unit **600** is also used for imaging directed multi-deflected ion beam **20** exiting ion beam directing and multi-deflecting
20 assembly **120** and being directed towards, incident and impinging upon, and milling, a surface of the work piece, as particularly shown in Fig. 14.

 Component imaging unit **600** is operatively connected to vacuum chamber assembly **210**. Component imaging unit **600** has as main component a video camera, generally indicated by **600** in Figs. 12, 13, and 14. Preferably, electronics and process
25 control utilities **800** is operatively connected to component imaging unit **600**, for providing electronics to, and enabling process control of component imaging unit **600**.

 With reference to Fig. 11, system **70**, optionally, and preferably, includes at least one work piece analytical unit **700**, for analyzing the work piece. In general, system **70**, including ion beam unit **100** and vacuum unit **200**, and at least one work piece analytical
30 unit **700**, is particularly implementable for analyzing a wide variety of different types of work pieces, particularly in the form of samples or materials, such as those derived from semiconductor wafers or chips, that are widely used in the above indicated exemplary fields.

Ordinarily, each work piece analytical unit **700** is at least partly operatively connected to vacuum chamber assembly **210** of vacuum unit **200**. Preferably, electronics and process control utilities **800** is operatively connected to each work piece analytical unit **700**, for providing electronics to, and enabling process control of, each work piece analytical unit **700**.

Work piece analytical unit **700** is, for example, a SIMS (secondary ion mass spectrometer) using directed multi-deflected ion beam **20**, of ion beam unit **100**, which is incident and impinges upon (without necessarily milling) a surface of the work piece. For such an exemplary specific embodiment of system **70**, vacuum unit **200** preferably includes assemblies and related equipment for providing and maintaining ultra-high vacuum conditions, for example, with a vacuum environment having a pressure as low as about 10^{-10} Torr, in vacuum chamber assembly **210**. which include components of the SIMS. Alternatively, work piece analytical unit **700** is an EDS (energy dispersion spectrometer) using a beam of primary electrons **PE** generated by SEM column assembly **310** of work piece imaging and milling detection unit **300**.

In system **70**, wherein optionally, and preferably, there is included work piece imaging and milling detection unit **300**, then SEM column assembly **310** included therein, can also function for physically analyzing the surface of the work piece. Alternatively, or additionally, SEM column assembly **310** can operate in STEM mode by utilizing transmitted electron detector assembly **340** of work piece imaging and milling detection unit **300**, for the work piece being transparent to electrons, for physically analyzing the bulk material of the work piece.

In system **70**, electronics and process control utilities **800**, in addition to providing electronics to, and enabling process control of, ion beam unit **100** and vacuum unit **200**, is for providing electronics to, and enabling process control of, the optional additional operatively connected system units.

Electronics and process control utilities **800**, in addition to being operatively connected to ion beam unit **100** and to vacuum unit **200**, is operatively connected to each optional additional unit, that is, work piece imaging and milling detection unit **300**, work piece manipulating and positioning unit **400**, anti-vibration unit **500**, component imaging unit **600**, or/and at least one work piece analytical unit **700**, of system **70**.

Electronics and process control utilities **800** has any number of the following main components: a central control panel or board, at least one computer, microprocessor, or

central processing unit (CPU), along with associated computer software, power supplies, power converters, controllers, controller boards, various printed circuit boards (PCBs), for example, including input/output (I/O) and D/A (digital to analog) and A/D (analog to digital) functionalities, cables, wires, connectors, shieldings, groundings, various electronic
5 interfaces, and network connectors.

With reference to Figs. 4 and 9, electronics and process control utilities **800** is operatively connected and integrated with the various power supplies of ion beam unit **100**, in general, and in particular, the power supplies of ion beam source assembly **110**, and ion beam directing and multi-deflecting assembly **120**.

Another main aspect of the present invention is a sub-combination of the system for directed multi-deflected ion beam milling of a work piece, whereby there is provision of a system for directed multi-deflecting a provided ion beam, including the following main components and functionalities thereof: an ion beam unit, wherein the ion beam unit includes an ion beam directing and multi-deflecting assembly, for directing and at least
15 twice deflecting the provided ion beam, for forming a directed multi-deflected ion beam; the ion beam directing and multi-deflecting assembly includes an ion beam first deflecting assembly, for deflecting and directing the provided ion beam, for forming a directed once deflected ion beam, and an ion beam second deflecting assembly, for deflecting and directing the directed once deflected ion beam, for forming a directed twice deflected ion
20 beam being a type of the multi-deflected ion beam; and a vacuum unit, operatively connected to the ion beam unit, for providing and maintaining a vacuum environment for the ion beam unit.

Accordingly, with reference to Figs. 2 - 14, the system for directed multi-deflecting a provided ion beam includes the following main components and functionalities thereof:
25 an ion beam unit **100**, as illustratively described hereinabove, wherein ion beam unit **100** includes an ion beam directing and multi-deflecting assembly **120**, for directing and at least twice deflecting the provided ion beam **10**, for forming a directed multi-deflected ion beam **20**, the ion beam directing and multi-deflecting assembly **120** includes an ion beam first deflecting assembly **122**, for deflecting and directing the provided ion beam **10**, for
30 forming a directed once deflected ion beam **16**, and an ion beam second deflecting assembly **124**, for deflecting and directing the directed once deflected ion beam **16**, for forming a directed twice deflected ion beam **20** being a type of the multi-deflected ion

beam; and a vacuum unit **200**, operatively connected to the ion beam unit **100**, for providing and maintaining a vacuum environment for the ion beam unit **100**.

Another main aspect of the present invention is provision of a method for determining and controlling extent of ion beam milling of a work piece, including the following main steps, and, components and functionalities thereof: providing a set of pre-determined values of at least one parameter of the work piece selected from the group consisting of: thickness of the work piece, depth of a target within the work piece, and topography of at least one surface of the work piece; performing directed multi-deflected ion beam milling of the work piece using a method for the directed multi-deflected ion beam milling of a work piece, including the following main steps, and, components and functionalities thereof: providing an ion beam; and directing and at least twice deflecting the provided ion beam, for forming a directed multi-deflected ion beam, wherein the directed multi-deflected ion beam is directed towards, incident and impinges upon, and mills, a surface of the work piece; real time measuring in-situ the at least one parameter of the work piece, for forming a set of measured values of the at least one parameter; comparing the set of the measured values to the provided set of the pre-determined values, for forming a set of value differences associated with the comparing; feeding back the set of the value differences for continuing the performing directed multi-deflected ion beam milling of the work piece, until the value differences are within a pre-determined range.

In the method for determining and controlling extent of ion beam milling of a work piece, the degree of selectivity of the at least one surface of the work piece corresponds to the topography as being one of the pre-determined parameters of the work piece.

The method for determining and controlling extent of ion beam milling of a work piece, is according to a closed-loop feedback control of the three parameters: thickness of the work piece, depth of a target **90** within the work piece, and topography of at least one surface of the work piece. There are known methods for measuring (determining) the thickness, however, the present method provides the ability to perform real-time, in-situ control of these parameters, and to do so in an automated manner, whereby ion beam milling of the work piece is controlled to end at a pre-determined thickness, with target **90** positioned at a pre-determined depth, and to have the bordering surfaces (top and bottom) have a controlled topography, either with or without selectivity, including extent of the selectivity, and for these surfaces to be either (preferably) parallel, or without a pre-determined offset angle in reference to the longitudinal axis **40**.

This control is enabled by the method of static work piece, directed multi-deflected ion beam milling, and real-time, in-situ SEM/STEM imaging (with best resolution), including use of SE, BSE and TE detectors, either in combination, or separately. In another exemplary specific preferred embodiment, this control is enabled by involving the work piece manipulating and positioning unit **400** to change the position of the work piece, either by rotating the work piece in relation to the longitudinal axis **40** by 180 degrees, in order to allow either of top or bottom surfaces of the work piece to be imaged by the electron beam of the SEM. An exemplary method for controlling the depth of a target **90** in the work piece is to tilt the work piece by means of the work piece manipulating and positioning unit **400** and to register the corresponding shift, ΔL , of target **90** as imaged by the transmitted electron detector **340** of the work piece imaging and milling detection unit **300**, in comparison to the non-tilted image **92** of target **90**. The depth of target **90** within the work piece is calculated from the angle of tilt, herein, referred to as β , and the degree or extent of shift of the image **92** of target **90**, as shown in Figs. 16, 17a, and 17b.

Fig. 16 is a schematic diagram illustrating a combined cross-section view (upper part (a)) and top view (lower part (b)) of using the exemplary specific preferred embodiment of the work piece imaging and milling detection unit **300**, and main components thereof, along with the ion beam unit **100**, and the work piece manipulating and positioning unit **400**, as part of system **70** illustrated in Figs. 11, 12, and 13, in relation to the work piece, illustrated in Fig. 14, for determining and controlling extent of ion beam milling of a work piece. In Fig. 16, **80** refers to the projection of the detector segments, that is, **342**, **344**, and **346**, of transmitted electron detector assembly **340**, wherein each detector segment operates as an independent detector, each operatively connected to an separate electronic circuit, part of electronics and process control utilities **800** of system **70**. The signals from detector segments, that is, **342**, **344**, and **346**, of transmitted electron detector assembly **340**, can be used for measuring or imaging, according to any desired combination, in particular, as relating to bright field and dark field STEM images.

Figs. 17a and 17b are schematic diagrams illustrating a cross-section view of determining depth of a target **90** within a milled work piece, as part of determining and controlling extent of ion beam milling of a work piece, using the transmitted electron detector assembly included in the work piece imaging and milling detection unit illustrated in Figs. 14 and 16.

Based upon the above indicated aspects of novelty and inventiveness, and, beneficial and advantageous aspects, characteristics, or features, the present invention successfully overcomes limitations, and widens the scope, of presently known techniques of ion beam milling.

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It is appreciated that certain aspects and characteristics of the invention, which are, for clarity, described in the context of separate embodiments, may also be provided in combination in a single embodiment. Conversely, various aspects and characteristics of the invention, which are, for brevity, described in the context of a single embodiment, may also
10 be provided separately or in any suitable sub-combination.

All publications, patents and patent applications mentioned in this specification are herein incorporated in their entirety by reference into the specification, to the same extent as if each individual publication, patent or patent application was specifically and
15 individually indicated to be incorporated herein by reference. In addition, citation or identification of any reference in this application shall not be construed as an admission that such reference is available as prior art to the present invention.

While the invention has been described in conjunction with specific embodiments
20 and examples thereof, it is evident that many alternatives, modifications and variations will be apparent to those skilled in the art. Accordingly, it is intended to embrace all such alternatives, modifications and variations that fall within the spirit and broad scope of the appended claims.

25

WHAT IS CLAIMED IS:

1. A method for directed multi-deflected ion beam milling of a work piece, comprising:

providing an ion beam; and

directing and at least twice deflecting said provided ion beam, for forming a directed multi-deflected ion beam, wherein said directed multi-deflected ion beam is directed towards, incident and impinges upon, and mills, a surface of the work piece.

2. The method of claim 1, wherein said directing and at least twice deflecting said provided ion beam includes deflecting and directing said provided ion beam, for forming a directed once deflected ion beam, and, deflecting and directing said directed once deflected ion beam, for forming a directed twice deflected ion beam.

3. The method of claim 2, wherein said directed twice deflected ion beam is a type of said multi-deflected ion beam.

4. The method of claim 1, wherein said directing and at least twice deflecting said provided ion beam includes focusing and directing said provided ion beam, for forming a directed focused ion beam.

5. The method of claim 4, wherein said focusing and directing said provided ion beam includes deflecting said provided ion beam as part of said forming said directed focused ion beam.

6. The method of claim 1, wherein said directing and at least twice deflecting said provided ion beam includes extracting and directing said provided ion beam, for forming a directed extracted ion beam.

7. The method of claim 2, wherein said directing and at least twice deflecting said provided ion beam includes deflecting and directing said directed twice deflected ion beam, for forming a directed thrice deflected ion beam.

8. The method of claim 7, wherein said directed thrice deflected ion beam is a type of said multi-deflected ion beam.

9. A method for directed multi-deflecting a provided ion beam, comprising: directing and at least twice deflecting the provided ion beam, for forming a directed multi-deflected ion beam, by deflecting and directing the provided ion beam, for forming a directed once deflected ion beam, and, deflecting and directing said directed once deflected ion beam, for forming a directed twice deflected ion beam being a type of said directed multi-deflected ion beam.

10. The method of claim 9, wherein said directing and at least twice deflecting the provided ion beam includes focusing and directing the provided ion beam, for forming a directed focused ion beam.

11. The method of claim 10, wherein said focusing and directing the provided ion beam includes deflecting the provided ion beam as part of said forming said directed focused ion beam.

12. The method of claim 9, wherein said directing and at least twice deflecting the provided ion beam includes extracting and directing the provided ion beam, for forming a directed extracted ion beam.

13. The method of claim 9, wherein said directing and at least twice deflecting the provided ion beam includes deflecting and directing said directed twice deflected ion beam, for forming a directed thrice deflected ion beam being another said type of said multi-deflected ion beam.

14. A method for determining and controlling extent of ion beam milling of a work piece, comprising:

providing a set of pre-determined values of at least one parameter of the work piece selected from the group consisting of: thickness of the work piece, depth of a

target within the work piece, and topography of at least one surface of the work piece;

performing directed multi-deflected ion beam milling of the work piece using a method for directed multi-deflected ion beam milling of a work piece, including the following main steps, and, components and functionalities thereof: providing an ion beam; and directing and at least twice deflecting the provided ion beam, for forming a directed multi-deflected ion beam, wherein the directed multi-deflected ion beam is directed towards, incident and impinges upon, and mills, a surface of the work piece;

real time measuring in-situ said at least one parameter of the work piece, for forming a set of measured values of said at least one parameter;

comparing said set of said measured values to said provided set of said pre-determined values, for forming a set of value differences associated with said comparing;

feeding back said set of said value differences for continuing said performing directed multi-deflected ion beam milling of the work piece, until said value differences are within a pre-determined range.

15. The method of claim 14, wherein degree of selectivity of said at least one surface of the work piece corresponds to said topography of the work piece.

16. A device for directed multi-deflected ion beam milling of a work piece, comprising:

an ion beam source assembly, for providing an ion beam; and

an ion beam directing and multi-deflecting assembly, for directing and at least twice deflecting said provided ion beam, for forming a directed multi-deflected ion beam, wherein said directed multi-deflected ion beam is directed towards, incident and impinges upon, and mills, a surface of the work piece.

17. The device of claim 16, wherein said ion beam directing and multi-deflecting assembly includes an ion beam first deflecting assembly, for deflecting and directing said provided ion beam, for forming a directed once deflected ion beam, and

an ion beam second deflecting assembly, for deflecting and directing said directed once deflected ion beam, for forming a directed twice deflected ion beam.

18. The device of claim 17, wherein said directed twice deflected ion beam is a type of said multi-deflected ion beam.

19. The device of claim 16, wherein said ion beam directing and multi-deflecting assembly includes an ion beam focusing assembly, for focusing and directing said provided ion beam, for forming a directed focused ion beam.

20. The device of claim 19, wherein said ion beam focusing assembly includes an ion beam deflecting sub-assembly, for deflecting said provided ion beam as part of said forming said directed focused ion beam.

21. The device of claim 16, wherein said ion beam directing and multi-deflecting assembly includes an ion beam extractor assembly, for extracting and directing said provided ion beam, for forming a directed extracted ion beam.

22. The device of claim 17, wherein said ion beam directing and multi-deflecting assembly includes an ion beam third deflecting assembly, for deflecting and directing said directed twice deflected ion beam, for forming a directed thrice deflected ion beam.

23. The device of claim 22, wherein said directed thrice deflected ion beam is a type of said multi-deflected ion beam.

24. A device for directed multi-deflecting a provided ion beam, comprising:
an ion beam directing and multi-deflecting assembly, for directing and at least twice deflecting the provided ion beam, for forming a directed multi-deflected ion beam, wherein said ion beam directing and multi-deflecting assembly includes an ion beam first deflecting assembly, for deflecting and directing the provided ion beam, for forming a directed once deflected ion beam, and an ion beam second deflecting assembly, for deflecting and directing said directed once

deflected ion beam, for forming a directed twice deflected ion beam being a type of said directed multi-deflected ion beam.

25. The device of claim 24, wherein said ion beam directing and multi-deflecting assembly further includes an ion beam focusing assembly, for focusing and directing the provided ion beam, for forming a directed focused ion beam.

26. The device of claim 25, wherein said ion beam focusing assembly includes an ion beam deflecting sub-assembly, for deflecting the provided ion beam as part of said forming said directed focused ion beam.

27. The device of claim 25, wherein said ion beam directing and multi-deflecting assembly further includes an ion beam extractor assembly, for extracting and directing the provided ion beam, for forming a directed extracted ion beam.

28. The device of claim 25, wherein said ion beam directing and multi-deflecting assembly further includes an ion beam third deflecting assembly, for deflecting and directing said directed twice deflected ion beam, for forming a directed thrice deflected ion beam being another said type of said directed multi-deflected ion beam.

29. A system for directed multi-deflected ion beam milling of a work piece, comprising:

an ion beam unit, wherein said ion beam unit includes an ion beam source assembly, for providing an ion beam, and an ion beam directing and multi-deflecting assembly, for directing and at least twice deflecting said provided ion beam, for forming a directed multi-deflected ion beam, wherein said directed multi-deflected ion beam is directed towards, incident and impinges upon, and mills, a surface of the work piece; and

a vacuum unit, operatively connected to said ion beam unit, for providing and maintaining a vacuum environment for said ion beam unit and the work piece, wherein said vacuum unit includes the work piece.

30. The system of claim 29, wherein said ion beam directing and multi-deflecting assembly includes an ion beam first deflecting assembly, for deflecting and directing said provided ion beam, for forming a directed once deflected ion beam, and an ion beam second deflecting assembly, for deflecting and directing said directed once deflected ion beam, for forming a directed twice deflected ion beam.

31. The system of claim 30, wherein said directed twice deflected ion beam is a type of said multi-deflected ion beam.

32. The system of claim 30, wherein said ion beam directing and multi-deflecting assembly includes an ion beam focusing assembly, for focusing and directing said provided ion beam, for forming a directed focused ion beam.

33. The system of claim 32, wherein said ion beam focusing assembly includes an ion beam deflecting sub-assembly, for deflecting said provided ion beam as part of said forming said directed focused ion beam.

34. The system of claim 30, wherein said ion beam directing and multi-deflecting assembly includes an ion beam extractor assembly, for extracting and directing said provided ion beam, for forming a directed extracted ion beam.

35. The system of claim 30, wherein said ion beam directing and multi-deflecting assembly includes an ion beam third deflecting assembly, for deflecting and directing said directed twice deflected ion beam, for forming a directed thrice deflected ion beam.

36. The system of claim 35, wherein said directed thrice deflected ion beam is a type of said multi-deflected ion beam.

37. The system of claim 30, further comprising electronics and process control utilities, operatively connected to said ion beam unit and said vacuum unit, for providing electronics and process control to said ion beam unit and said vacuum unit.

38. The system of claim 30, further comprising at least one additional unit selected from the group consisting of: a work piece imaging and milling detection unit, a work piece manipulating and positioning unit, an anti-vibration unit, a component imaging unit, and at least one work piece analytical unit, wherein each said additional unit is operatively connected to said vacuum unit.

39. A system for directed multi-deflecting a provided ion beam, comprising:
an ion beam unit, wherein said ion beam unit includes an ion beam directing and multi-deflecting assembly, for directing and at least twice deflecting the provided ion beam, for forming a directed multi-deflected ion beam, said ion beam directing and multi-deflecting assembly includes an ion beam first deflecting assembly, for deflecting and directing the provided ion beam, for forming a directed once deflected ion beam, and an ion beam second deflecting assembly, for deflecting and directing said directed once deflected ion beam, for forming a directed twice deflected ion beam being a type of said multi-deflected ion beam;
and
a vacuum unit, operatively connected to said ion beam unit, for providing and maintaining a vacuum environment for said ion beam unit.

40. The system of claim 39, wherein said ion beam directing and multi-deflecting assembly further includes an ion beam focusing assembly, for focusing and directing the provided ion beam, for forming a directed focused ion beam.

41. The system of claim 40, wherein said ion beam focusing assembly includes an ion beam deflecting sub-assembly, for deflecting the provided ion beam as part of said forming said directed focused ion beam.

42. The system of claim 40, wherein said ion beam directing and multi-deflecting assembly further includes an ion beam extractor assembly, for extracting and directing the provided ion beam, for forming a directed extracted ion beam.

43. The system of claim 40, wherein said ion beam directing and multi-deflecting assembly further includes an ion beam third deflecting assembly, for

deflecting and directing said directed twice deflected ion beam, for forming a directed thrice deflected ion beam being another said type of said multi-deflected ion beam.

44. The system of claim 40, further comprising electronics and process control utilities, operatively connected to said ion beam unit and said vacuum unit, for providing electronics and process control to said ion beam unit and said vacuum unit.

45. The system of claim 40, further comprising at least one additional unit selected from the group consisting of: a work piece imaging and milling detection unit, a work piece manipulating and positioning unit, an anti-vibration unit, a component imaging unit, and at least one work piece analytical unit, wherein each said additional unit is operatively connected to said vacuum unit.