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(71) Applicants (*for all designated States except US*): **APPLIED MATERIALS ISRAEL, LTD.** [IL/IL]; 8 Oppenheimer Street, 76236 Rehovot (IL). **APPLIED MATERIALS, INC.** [US/US]; P.O. Box 450A, Santa Clara, CA 95052 (US). **INTERNATIONAL BUSINESS MACHINES CORPORATION** [US/US]; 1133 Westchester Avenue, White Plains, NY 10604 (US).

(72) Inventors; and
(75) Inventors/Applicants (*for US only*): **ADAN, Ofer** [IL/IL]; 3 Israel Aharoni St. Apt 3, 76281 Rehovot (IL). **CORNELL, Roger, Steele** [US/US]; 11 Hartstone Drive, Poughkeepsie, NY 12603 (US). **ROSENBERG, Zvika** [IL/IL]; 2 Hashikma St., 90805 Mevaseret Zion (IL). **EYTAN, Guy** [IL/IL]; 48 Ehud St., 73134 Menora (IL). **ARCHIE, Charles** [US/US]; 34 Raemont Road, Granite Springs, NY 10527 (US). **SOLECKY, Eric** [US/US]; 45 Mansion Drive, Hyde Park, NY 12538 (US). **MAYER, Jason** [US/US]; 465 Bedford Road Apt. 3R, Pleasantville, NY 10570 (US).

(74) Agent: **FAHMI, Tarek, N.**; Blakely, Sokoloff, Taylor & Zafman LLP, 12400 Wilshire Boulevard, 7th Floor, Los Angeles, CA 90025 (US).

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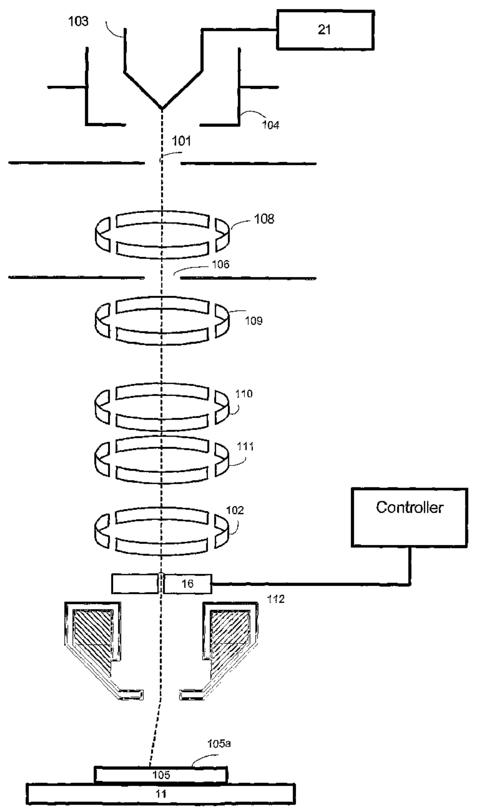
# (54) Title: A METHOD FOR MEASURING AND REDUCING ANGULAR DEVIATIONS OF A CHARGED PARTICLE BEAM




**(57) Abstract:** The invention provides a system and method for determining an angular deviation of a charged particle beam and for calibrating a charged particle beam system that are based upon multiple measurements of a test object that include sidewalls of high sidewall angle uniformity. A path of a charged particle beam is controlled by multiple beam control parameters. The method determines the parameters that will substantially reduce the angular deviation and applies them in order to calibrate a charged particle beam system.

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# A METHOD FOR MEASURING AND REDUCING ANGULAR DEVIATIONS OF A CHARGED PARTICLE BEAM

## RELATED APPLICATIONS

[001] This application claims the priority of U.S provisional application serial number 60/445,780, filed 5th February 2003, entitled "Stray tilt measurement and reduction".

## FIELD OF THE INVENTION

[002] This invention relates to system and method for inspecting semiconductors wafers during circuit fabrication and, in particular, for measuring angular deviations and reducing angular deviations.

## BACKGROUND

[003] Integrated circuits are very complex devices that include multiple layers. Each layer may include conductive material and/or isolating material while other layers may include semi-conductive materials. These various materials are arranged in patterns, usually in accordance with the expected functionality of the integrated circuit. The patterns also reflect the manufacturing process of the integrated circuits.

[004] Various inspection and failure analysis techniques evolved for inspecting integrated circuits during the manufacturing process. Various optical as well as charged particle beam inspection tools and review tools are known in the art, such as the VeraSEM™, Complus™ and SEMVision™ of Applied Materials Inc. of Santa Clara, California.

[005] Manufacturing failures may affect the electrical characteristics of the integrated circuits. Some of these failures result from unwanted deviations from the

required dimensions of the patterns. A "critical dimension" (CD) is the width of a patterned line or the distance between two patterned lines. A scanning electron microscopes that measures critical dimensions is also referred to as CD-SEM.

[006] One of the goals of the inspection process is to determine whether the inspected wafer includes deviations from these critical dimensions. This inspection usually includes scanning sub-micron structural elements with electron beams, detecting electrons that are omitted as a result of said scan and processing the detected electrons to determine the critical dimensions.

[007] Modern CD-SEMs are able to measure structural elements that have cross sections that have sub-micron dimensions, with an accuracy of several nanometers. The size of these cross section is expected to reduce in the future, as manufacturing and inspection processes continue to improve.

[008] U.S patent 6420703 of Wa, et al. titled "Method for forming a critical dimension SEM calibration standard of improved definition and standard formed" describes a method for producing a calibration standard that includes multiple metal lines that have a line width uniformity of less than 20 nanometers in a length of 20 microns. Wa is an evidence of the ability of manufacture very accurate test structures.

[009] U.S patent 6570157 of Singh, et al titled "Multi-pitch and line calibration for mask and wafer CD-SEM system" describes a reference that has multiple features thus facilitating a CD-SEM calibration process that is responsive to measurements of multiple features. Singh claims that the measurement of multiple features reduces

the susceptibility to degradation of calibration standards resulting from multiple measurements.

[0010] U.S patent 6559446 of Choo et al., titled "System and method for measuring dimensions of a feature having a re-entrant profile" describes a system and method for measuring a cross-section characteristic of a feature that involves two scans of a feature at opposing angles relative to an imaginary line drawn perpendicular to the images substrate. Choo does not address the problem of angular deviation. Those of skill in the art will appreciate that due to unwanted angular deviation of the electron beam the angles are not exactly opposite to each other.

[0011] U.S patent 6472662 of Archie titled "Automated method for determining several critical dimension properties from scanning electron microscope by using several tilted beam or sample scans" provides a method for critical dimension measurement that involves illuminating a test object by multiple tilted beams and processing the detected waveforms to define critical dimensions.

[0012] Within a CD-SEM the electron beam path is controlled by multiple deflection units that are responsive to beam control parameters. Due to various reasons, such as mechanical and electrical imperfections, electron beams that are expected to be oriented at a certain angle in respect to a tested object, are slightly deviated. This angular deviation may result in measurement inaccuracies.

[0013] There is a need to provide an efficient method and system for measuring angular deviation of electron beams.

[0014] There is a need to provide a method and system for calibrating scanning electron microscopes such as to substantially reduce (or even eliminate) the angular deviation.

**SUMMARY OF THE INVENTION**

[0015] The invention provides a method for determining an angular deviation of a charged particle beam, the method includes the steps of: (i) providing a test object that includes a structural element that has multiple sidewalls; (ii) measuring a feature of at least one sidewall of the structural element; changing the relationship between the charged particle beam and the test object; (iii) measuring a feature of at least one sidewall of the structural element; and (iv) processing the measurements to determine the angular deviation of the charged particle beam. Conveniently, the measurements are performed at sidewall portions that are characterized by a small angular variation.

[0016] The invention provides a method for determining an angular deviation of a charged particle beam, the method includes the steps of: (i) providing a test object that includes a structural element that has multiple sidewalls; (ii) measuring a feature of at least one sidewall of the structural element; (iii) introducing a rotational movement between the charged particle beam and the test object; (iv) measuring a feature of at least one sidewall of the structural element; and (v) processing the measurements to determine the angular deviation of the charged particle beam. Conveniently, the measurements are performed at sidewall portions that are characterized by a small angular variation.

[0017] The invention provides a method for determining an angular deviation of a charged particle beam, the method includes the steps of: (i) providing a test object that includes a first and second substantially equal structural elements, each structural element includes multiple sidewalls; (ii) measuring a feature of at least one sidewall of a first structural element; (iii) changing a relationship between the charged particle beam and the test object; (iv) measuring a feature of at least one sidewall of the second structural element; and (v) processing the measurements to determine the angular deviation of the charged particle beam; whereas each sidewall of the at least one measured sidewall is characterized by a small angular variation.

[0018] The invention provides a method for calibrating a charged particle beam system, the method includes the steps of: (i) setting a charged particle beam to a certain tilt state; (ii) determining calibrated beam control parameters values; (iii) and changing the certain tilt state and repeating the step of determining a calibrated beam control parameters.

[0019] The invention provides a method for determining an angular deviation of a charged particle beam, the method includes the steps of: (i) providing a test object that includes a first and a second structural elements that are oriented towards each other by a first planar angle $\alpha 1$; whereas the first structural element has a first sidewall that is oriented at a first sidewall angle $\beta 1$; whereas the second structural element had a second sidewall that is oriented at a second sidewall angle $\beta 2$; (ii) measuring a feature of the first sidewall by scanning the first sidewall with a charged particle beam whereas the angular orientation between the charged particle beam and the first sidewall is greater than $\beta 1$; (iii) measuring a feature of the second sidewall by scanning the second sidewall with a charged particle beam whereas the angular orientation between the charged particle beam and the second sidewall is greater than $\beta 2$; (iv) measuring a feature of the first sidewall by scanning the first sidewall with a charged particle beam whereas the angular orientation between the charged particle beam and the first sidewall is smaller than $\beta 1$; (v) measuring a feature of the second sidewall by scanning the first sidewall with an charged particle beam whereas the angular orientation between the charged particle beam and the second sidewall is smaller than $\beta 2$; and (vi) determining the angular deviation in response to the measurements.

[0020] The invention provides a system for determining an angular deviation of a charged particle beam, the system includes: (i) means for performing at least two measurements of a feature of a structural element of a test object whereas each measurement involves an interaction between the test object and a charged particle beam; and whereas the measurements differ from each other by a relationship between a charged particle beam and the test structure; and (ii) means for processing the at least two measurements for determining the angular deviation.

## BRIEF DESCRIPTION OF THE DRAWINGS

[0021] In order to understand the invention and to see how it may be carried out in practice, a preferred embodiment will now be described, by way of non-limiting example only, with reference to the accompanying drawings, in which:

[0022] Figure 1a and 1b are schematic illustrations of a CD-SEM and of a objective lens and tilt mechanism, in accordance with an embodiment of the invention;

[0023] Figures 2 - 4 illustrate a test object and multiple structural elements, in various scales, in accordance with an embodiment of the invention;

[0024] Figures 5a - 5b illustrate an inspected structural element and electron beams that are used to scan the structural elements at different tile angles; in accordance with an embodiment of the invention;

[0025] Figure 6 is a flow charts of method for determining an angular deviation of an electron beam, in accordance with an embodiment of the invention;

[0026] Figures 7-8 are flow charts of methods for calibrating a scanning electron microscope, in accordance with an embodiment of the invention; and

[0027] Figures 9-10 illustrate methods for utilizing a SEM, in accordance with an embodiment of the invention.

## DETAILED DESCRIPTION

[0028] The invention applies to charged particle beams such as ion beams and electron beams. For convenience of explanation the following detailed description refers to electron beams as well as to tools that utilize electron beams, without limiting the scope of the invention. Accordingly, although the invention related in general to charged particle beam systems (such as but not limited to Focused Ion Beam devices, Scanning Electron Microscopes and the like) that are capable of directing a charged particle beam towards a test object, the detailed description refers to Scanning Electron Microscopes and especially to CD-SEMs.

[0029] A typical CD-SEM includes an electron gun for generating an electron beam, deflection and tilt units for determining a path of an electron beam, focusing lens for focusing the electron beam onto an inspected object while reducing various aberrations and misalignments, detectors and processors.

[0030] Electrons, such as secondary electrons that are emitted as result of an interaction between the inspected object and the electron beam are attracted to a detector that provides detection signals that in turn are processed by a processing unit. The detection signals may be used to determine various features of the specimen, as well as form images of the inspected specimen.

[0031] The invention may be implemented on SEMS such as CD-SEMs of various architectures that may differ from each other by the amount of their components as well as the arrangement of said components. For example, the amount of deflection units, as well as the exact structure of each deflection unit may vary. The CD-SEM may include in-lens as well as out of lens detectors or a combination of both.

[0032] A block diagram of a critical dimension scanning electron microscope (CD-SEM) 100 is shown schematically in Fig. 1a. CD-SEM 100 includes an electron gun 103 emitting an electron beam 101, which is extracted by the anode 104. The objective lens 112 focuses the electron beam on the specimen surface 105a. The beam is scanned over the specimen using the scanning deflection unit 102.

[0033] An alignment of the beam to the aperture 106 or a desired optical axis respectively can be achieved by the deflection units 108 to 111. Each deflection unit may include coils and, alternatively or additionally, electrostatic modules such as charged plates.

[0034] Detector 16 is able to detect secondary electrons that escape from the specimen 105 at a variety of angles with relatively low energy (3 to 50 eV). Measurements of scattered or secondary electrons from a specimen can be conducted with detectors in the form of scintillators connected to photomultiplier tubes or the like. Since the way of measuring the signals does not influence the inventive idea in general, this is not to be understood as limiting the invention.

[0035] Detection signals are processed by a processing unit (that may be a part of controller 33, but this is not necessarily so). The processing unit may have image processing capabilities and is able to process the detection signals in various manners. Usually, the processing unit includes dedicated signal processing hardware and software.

[0036] A typical processing scheme includes generating a waveform that reflects the amplitude of the detection signal versus the scan direction. The waveform is further processed to determine locations of at least one edge, and other cross sectional features of inspected structural elements.

[0037] The different parts of the system are connected to corresponding supply units (such as high voltage supply unit 21) that are controlled by various control units, most of them are omitted from the figure for simplifying the explanation. The control units may determine the current supplied to a certain part, as well as the voltage.

[0038] CD-SEM 100 includes a double deflection system that includes deflection units 110 and 111. Thus, the beam tilt introduced in the first deflection unit 110, can be corrected for in the second deflection unit 111. Due to this double deflection system, the electron beam can be shifted in one direction without introducing a beam tilt of the electron beam with respect to the optical axis.

[0039] The inventors found that each deflection unit can introduce an angular deviation. The angular deviation may also be dependent upon the tilt state of the electron beam. Accordingly, in order to determine the angular deviation and especially in order to determine the relationship between the angular deviation and the beam control parameters (such as voltage, current supplied to a deflection unit) multiple angle deviation detection session as well as calibration sessions may be required. This relationship is usually defined by multiple coefficients.

[0040] Figure 1b is a perspective view of an objective lens 120 according to another embodiment of the invention. In figure 1b the tilt deflection is performed below (downstream direction) of the objective lens. Objective lens differs from objective lens 102 by having a pole-piece arranged in a quadruple formation, positioned between the objective lens and specimen, for controlling the tilt condition of the electron beam. The pole-pieces are electrically connected to a ring and a core that bears additional coils (not shown) that are arranged such as to concentrate a magnetic flux at the space between the pole-pieces, through which the electron beam passes.

[0041] Figure 2-4 illustrate test object 200 and some of its portions 210'. The inventors used a Q-Cleave-D wafer produced by Sematech as a test object, but other test objects can also be used. A test object has to be characterized by having multiple sidewalls, whereas measured sidewalls must be characterized by a high sidewall angle uniformity. This uniformity is expected to improve as time goes by, due to continuous improvements in the manufacturing processes of test objects. The angle may vary between sidewalls.

[0042] Test object 200 is planar wafer that includes multiple dies 220. The dies include multiple structural elements, such as "L" shaped structural elements 120. The sidewalls of some of these "L" shaped structural elements are measured during the calibration process. It is noted that the measured structural elements may be located within scribe lines.

[0043] It is further noted that although the previous figures illustrated L shaped structural elements, other shaped structural elements may be used, even a single line or a combination of lines can be regarded as a structural element.

[0044] The inventors found that the determination of an angular deviation of an electron beam can be implemented by measuring certain features of structural elements, altering the relationship between the structural elements and the electron beam, and performing additional measurements.

[0045] According to an embodiment of the invention this alteration is implemented without substantially changing the beam control parameters.

[0046] Conveniently, the alteration involves mechanically rotating (or otherwise moving) the test object (by moving the stage) and additionally or alternatively, moving the CD-SEM column (that include the electron gun, objective lens, deflection units, supply units and the like). The inventors rotated the test object by 180 degrees, but other rotational movements can also be used.

[0047] Usually, after the mechanical movement is introduced, a step of locating the previously measured structural element is performed by identifying unique characteristics of the element or another nearby element. This process can be automated by using well known location techniques that include a first step of locating a search area in which the structural element is located, by using the coordinates of the structural element and by performing an image recognition based search for the previously measured structural element. This location step can be characterized by a certain location inaccuracy.

[0048] The inventors found that there is a link between the location inaccuracy, rotation inaccuracy, test structure angular uniformity and the angular deviation measurement accuracy. Larger location inaccuracies and lower structural element sidewall angular uniformity (e.g. : higher structural element sidewall variation)may result in lower angular deviation measurement accuracy. Lower structural element sidewall angular uniformity can be compensated for by increasing location accuracy.

[0049] The inventors also found that the angular deviation measurement accuracy can be improved by performing measurements at multiple duplicate sites and statistically processing the results of the measurements. Accordingly, this statistical processing (for example averaging) can increase the accuracy of the measurement and can allow using structural elements that are characterized by higher angular variation.

[0050] The inventors found that by (i) measuring a feature of a structural element, (ii) rotating the structural element by 180 degrees and (iii) performing additional measurements of a feature of the structural element, various asymmetries in the structural elements are averaged out.

[0051] Figure 6 is a flow chart illustrating method 300 for determining an angular deviation of an electron beam. Method 300 starts at step 310 of providing a test object that includes a structural element that has multiple sidewalls. Some of these sidewalls are measured, and the measured sidewalls are characterized by small sidewall angle variation. Usually, this uniformity is responsive to the manufacturing process, so that all sidewalls share the same sidewall angle uniformity.

[0052] Sidewall angle non-uniformity can interfere with successful determination of the beam angular deviation. This non-uniformity can be parsed into two components: random variation from site to site and sample asymmetry differences. The asymmetry differences can also be called sample leaning, i.e., the structure is leaning like the leaning tower of Pisa. There are sampling strategies to deal with these two components. For site to site variation, this can be suppressed by making many measurements at similar sites and averaging the results. By the law of averages the uncertainty of the average is smaller than the uncertainty of a single measurement. The asymmetry difference can be removed by measuring the sample at the same physical location twice, separated by rotating the sample by 180 degrees. By returning to the same physical location to obtain measurements and averaging these measurements the sample asymmetry is cancelled out.

[0053] The test object may resemble test object 200 that includes multiple "L" shaped structural elements, but this is not necessarily so.

[0054] It is noted that the structural element may include two perpendicular lines, but may include lines that are not parallel yet not perpendicular to each other. Using an "L" shaped structural element simplifies calculations, especially when using Cartesian coordinates.

[0055] Step 310 is followed by step 330 of measuring a feature of at least one sidewall of the structural element. It is further noted that the measured feature is the width of the sidewall of the structural element, but other features may be measured.

[0056] Step 330 may include multiple measurements at multiple tilt states, depending upon the required measurement accuracy (more measurements may result in a more accurate result, as noise is averaged out), and whether the height of the structural element is known or estimated. If the height is known a single measurement is required, while if it is not known two measurements, at different tilt angles are required.

[0057] Step 330 is followed by step 350 of changing the relationship between the electron beam and the test object . Conveniently, this step does not involve a substantial change of beam control parameter and involves mechanical movement.

[0058] Step 350 is followed by step 370 of measuring the feature of at least one sidewall of the structural element.

[0059] The measurements of step 370 differs from the measurements of step 330 by the different relationship between the electron beam and the structural element. Referring to Figures 5a - 5b, illustrating a first structural element that has a first sidewall oriented at a first sidewall angle $\beta 1$. During step 330 the measurement angle between the electron bean and the measured structural element is $\delta 1$ while during step 370 the measurement angle is $\delta 2$. $\delta 1$= $\beta 1$ + □″ and $\delta 2$= $\beta 1$ - □″; whereas □″ is the angular deviation at a ZX plane, given a line that extends along the Y-axis within the XY plane.

[0060] Step 370 is followed by step 390 of processing the measurements of the feature to determine the angular deviation of the electron beam. The inventors found that the angular deviation can also be determined by processing measurements from more than a single tilt stage.

[0061] Usually step 310 is preceded by a preliminary step 302 of measuring the height of the structural element. The height may be determined by a two staged process of: (i) measuring the height of one or more structural elements in multiple locations to provide multiple height measurements, and (ii) statistically processing (such as by averaging, weighted averaging, standard deviation) the multiple height measurements to provide the height of the structural element. The amount of height measurements is responsive to a height measurement accuracy threshold. The height measurement can be done by the CD-SEM itself, by another CD-SEM tool or by other tools such as an atomic force microscope measurement.

[0062] According to an embodiment of the invention, once the angular deviation is determined, there is a need to calibrate the CD-SEM such as to substantially reduce that angular deviation.

[0063] The calibration process involves a determination of the relationship (usually defined by multiple coefficients) between the angular deviation of the electron beam and the beam control parameters. This relationship can be determined by performing multiple measurements of the angular deviation, whereas the amount of measurements can be responsive to the amount of unknown coefficients. Once the coefficients are known the beam control parameter values that substantially reduce (or even eliminate) the angular deviation can be calculated. Each of said multiple measurements may involve an execution of steps 330-390, with different beam control parameter values.

Assuming, for example, that an angular deviation is responsive to two beam control parameters - coil currents $I_X$ and $I_Y$, and that the relationship between the angular deviation and these parameters is defined by four coefficients ($A_{12}$, $C_X$ , $A_{21}$, $A_{22}$ and $C_Y$). In mathematical terms: $\square_X = A_{11}*I_X+A_{12}*I_Y+C_X$; $\square_Y = A_{21}*I_X+A_{22}*I_Y+C_Y$, whereas $\square_X$ is the x-component of the angular deviation, $\square_Y$ is the y-component of the angular deviation. Once the coefficients are found the current values that amount in substantially zero angular deviation can be determined. Referring to these equations, by setting $\square_X$ and $\square_Y$ to zero, the values of $I_{X0}$ and $I_{Y0}$ can be extracted. $I_{X0}$ and $I_{Y0}$ are the currents that substantially reduce the angular deviation, at a given voltage values and a certain tilt state.

[0064] According to an embodiment of the invention once these coefficients are known for a certain tilt stage they can be used during calibration of another tilt state. According to another embodiment of the invention once these coefficients are known for a certain electron beam energy they can be used to infer the calibration coefficients of another electron beam energy. According to yet a further embodiment of the invention once these coefficients are known for a certain tool they can be used for calibrating another tool. According to yet a further embodiment of the invention multiple coefficients can be gathered and be statistically process to provide better input to calibration sessions.

[0065] Figure 7 is a flow chart illustrating method 400 for calibrating a scanning electron microscope. Method 400 starts by step 410 of providing a test object that includes a first structural element and a second structural element. The first structural element has a first sidewall that is oriented at a first sidewall angle $\beta1$. The second structural element had a second sidewall that is oriented at a second sidewall angle $\beta2$.

[0066] It is noted that in figure 5B a single structural element has a first sidewall oriented at $\beta1$ and a second sidewall oriented at $\beta2$, but this is not necessarily so. Each structural element may have either the first or second sidewall. Alternatively, the test object may include multiple structural elements that may include one or both of these sidewalls.

[0067] Step 410 is followed by step 430 of measuring a feature of the first sidewall by scanning the first sidewall with an electron beam whereas the angular orientation between the electron beam and the first sidewall is greater than $\beta1$. For example, referring to Figures 5a and 5b, $\delta1= \beta1 + \square''$. Step 430 is followed by step 450 of measuring a feature of the second sidewall by scanning the second sidewall with an electron beam whereas the angular orientation between the electron beam and the second sidewall is greater than $\beta2$. For example, referring to Figures 5a and 5b, $\delta3= \beta2 + \square'$.

[0068] Step 450 is followed by step 470 of measuring a feature of the first sidewall by scanning the first sidewall with an electron beam whereas the angular orientation between the electron beam and the first sidewall is smaller than $\beta 1$.For example, referring to Figures 5a and 5b, $\delta 1= \beta 1$ - □″.

[0069] Step 470 is followed by step 490 of measuring a feature of the second sidewall by scanning the first sidewall with an electron beam whereas the angular orientation between the electron beam and the second sidewall is smaller than $\beta 2$.

For example, referring to Figures 5a and 5b, $\delta 3= \beta 2$ - □′.

[0070] It is noted that the order of the various measurement steps is not significant.

[0071] It is further noted that the inventors measured two perpendicular sidewalls of an L shaped structural element, and then rotated the test object (and the measured structural element) by 180 degrees, and performed measurements of the same sidewalls. The angular deviation along each axis was determined by averaging the first and second measurements of the same sidewall.

[0072] Step 490 is followed by step 495 of determining the angular deviation in response to the measurements.

[0073] Figure 8 is a flow chart illustrating method 500 for calibrating a scanning electron microscope. Method 500 starts by step 510 of setting an electron beam to a certain tilt state. This may obtained by mechanical and/or electrical adjustment of the scanning electron microscope and/or the stage (in case of mechanical adjustment).

[0074] Step 510 is followed by step 530 of determining a set of beam control parameter values that substantially reduce the angular deviation of the electron beam. Step 530 includes determining the relationship (usually coefficients) between the angular deviation of the electron beam and multiple beam control parameters and then determining beam control parameters values that substantially reduce the angular deviation of the electron beam (also referred to as calibrated beam control parameters values). The angular deviation is usually measured during one or more sessions of steps such as steps 310-390 or steps 430-495.

[0075] Step 530 is followed by step 550 of changing the certain tilt state and repeating the step of determining calibrated beam control parameters values.

[0076] As mentioned above, coefficients and/or calibrated beam control parameters values that are determined for a certain tilt state/certain electron beam energy can be used during another calibration process. They may used to provide an estimate that then can be used during another calibration process. The other calibration process may involve checking the estimate by measuring an angular deviation and either ending the calibration process or continuing the process until a desired angular deviation is achieved.

[0077] In an exemplary setting the inventors found the coefficients as well as the calibrated beam control parameters values that by performing five angular deviation measurements while providing deflection currents $I_X$ and $I_Y$ of different values: $(I_X=0, I_Y=0)$, $(I_X=I_{XMAX}/3, I_Y=0)$, $(I_X=2I_{XMAX}/3, I_Y=0)$, $(I_X=0, I_Y=I_{YMAX}/3)$ and $(I_X=0, I_Y=2I_{YMAX}/3)$. Whereas the currents $I_X$ and $I_Y$ affect the x-axis deflection and y-axis deflection of the electron beam. The maximal values of these currents are denoted $I_{XMAX}$ and $I_{YMAX}$. The measurements were made

[0078] Figures 9-10 illustrates methods 600 and 700 of utilizing a SEM.

[0079] Method 600 starts by step 610 of calibrating the SEM. Step 610 is followed by step 620 of applying beam control parameters for achieving a certain tilt state. Step 620 is followed by step 630 of measuring the angular deviation of the beam and step 640 of determining whether the certain tilt stage was achieved. If the certain tilt state was achieved then step 640 is followed by step 650 of measuring a sample, else step 640 is followed by step 660 of altering the beam control parameters values. Step 660 is followed by step 630. Step 630 may include one or more sessions of steps such as steps 310-390 or steps 430-495.

[0080] Method 700 starts by step 710 of setting the SEM to a certain tilt state. Step 710 is followed by step 720 of measuring the angular deviation of the beam. Step 720 is followed by step 730 of comparing the measurements to previous measurements from substantially the same tilt state. Step 730 is followed by step 740 determining whether to adjust the beam control parameters in response to the comparison, and if so step 740 is followed by step 750 of adjusting the beam control parameters values. Step 750 is followed by step 720. The process ends if step 740 determines that there is no need in further adjustments.

[0081] The inventors found that in some cased the alteration of beam control parameters values (for example the setting of calibrated beam control parameters values) may result in altering the characteristics of the charged particle beams, such as a change in focal point, change in magnification, change in various aberrations and the like. Accordingly, a step of compensating for these changes may be executed after these values are determined.

[0082] In cases where inspection and failure analysis processes are executed by multiple scanning electron microscopes (for example the CD-SEMS of a certain FAB, of a certain wafer fabrication process line, of a certain vendor), it is very useful to calibrate all devices by the same test object using the same method. The inventors found out that once a calibration session of a CD-SEM was completed the test object shall be used for calibration other CD-SEMs. According to an embodiment of the invention the results of the calibration process of a certain tool can be used for calibrating another tool.

[0083] The present invention can be practiced by employing conventional tools, methodology and components. Accordingly, the details of such tools, component and methodology are not set forth herein in detail. In the previous descriptions, numerous specific details are set forth, such as shapes of cross sections of typical lines, amount of deflection units, etc., in order to provide a thorough understanding of the present invention. However, it should be recognized that the present invention might be practiced without resorting to the details specifically set forth.

[0084] Only exemplary embodiments of the present invention and but a few examples of its versatility are shown and described in the present disclosure. It is to be understood that the present invention is capable of use in various other combinations and environments and is capable of changes or modifications within the scope of the inventive concept as expressed herein.

**We claim**

1. A method for determining an angular deviation of a charged particle beam, the method comprising the steps of:

providing a test object that comprises a structural element that has multiple sidewalls;

measuring a feature of at least one sidewall of the structural element;

changing the relationship between the charged particle beam and the test object;

measuring a feature of at least one sidewall of the structural element; and

processing the measurements to determine the angular deviation of the charged particle beam.

2. The method of claim 1 wherein the at least one sidewall measured during the first measuring step differs from the at least one sidewall measured during the second measuring step.

3. The method of claim 1 wherein a feature of at least a certain sidewall is measured during the first and second measurement steps.

4. The method of claim 1 wherein the measured feature is a width of a sidewall of the structural element.

5. The method of claim 1 further comprising a step of measuring the height of the structural element.

6. The method of claim 5 wherein the step of measuring the height comprises measuring heights of the structural element in multiple locations to provide multiple height measurements and statistically processing the multiple

height measurements to provide the height of the structural element.

7. The method of claim 6 wherein the amount of height measurements is responsive to a height measurement accuracy threshold.

8. The method of claim 5 wherein the measurement comprises an atomic force microscope measurement.

9. The method of claim 1 wherein the step of changing the relationship comprises introducing a relative movement between the charged particle beam and the test object.

10. The method of claim 1 wherein the step of changing the relationship involves introducing a relative rotational movement between the charged particle beam and the test object.

11. The method of claim 1 wherein during at least one measurement of a feature of a measured sidewall a measurement angle exceeds the sidewall angle and during at least another measurement of that feature the sidewall angle exceeds the measurement angle; whereas the measurement angle is defined between the charged particle beam and the measured sidewall.

12. The method of claim 1 further comprising a step of determining beam control parameters values in response to the angular deviation.

13. The method of claim 12 wherein the beam control parameters values comprise deflection unit current and voltage values.

14. The method of claim 12 wherein the beam control parameters values are calculated for different charged particle beam tilt states.

15. The method of step 12 further comprising calibrating charged particle beam deflectors in response to at least one charged particle beam coefficient.

16. The method of claim 1 wherein the structural element comprises two lines that are oriented towards each other by a first planar angle $\alpha 1$.

17. The method of claim 16 wherein $\alpha 1$ substantially equals ninety degrees.

18. The method of claim 1 wherein the test object comprises multiple structural elements and wherein the method further comprises measuring a feature of sidewalls of at least two structural elements to provide multiple measurements.

19. The method of claim 1 further comprising a step of locating the structural element by image base search.

20. The method of claim 1 wherein the charged particle beam can be positioned in multiple tilt states, and whereas the method further comprises determining the deviation angle of the charged particle beam for at least two tilt states.

21. The method of claim 1 wherein the charged particle beam is an electron beam.

22. The method of claim 1 wherein the charged particle beam is an ion beam.

23. The method of claim 1 wherein the angular deviation measurement is responsive to various inaccuracies.

24. The method of claim 23 wherein the inaccuracies comprise location inaccuracies, rotational inaccuracies, test structure angular non-uniformity and angular deviation measurement inaccuracies.

25. The method of claim 1 wherein the steps of measuring and changing are repeated to provide multiple angular deviation measurements that are processed to provide an angular deviation estimate.

26. The method of claim 25 wherein the amount of angular deviation measurements is responsive to various inaccuracies.

27. The method of claim 25 wherein the angular deviation measurements differ from each other by measurement locations.

28. The method of claim 1 wherein the measurements are performed at sidewall portions that are characterized by a small angular variation.

29. A method for determining an angular deviation of a charged particle beam, the method comprising the steps of:

providing a test object that comprises a structural element that has multiple sidewalls;

measuring a feature of at least one sidewall of the structural element;

introducing a rotational movement between the charged particle beam and the test object;

measuring a feature of at least one sidewall of the structural element; and

processing the measurements to determine the angular deviation of the charged particle beam.

30. The method of claim 29 wherein the measured feature is a width of a sidewall of the structural element.

31. The method of claim 29 further comprising a step of determining beam control parameters values in response to the angular deviation.

32. The method of claim 29 wherein the charged particle beam can be positioned in multiple tilt states, and whereas the method further comprises determining the deviation angle of the charged particle beam for at least two tilt states.

33. The method of claim 29 wherein the charged particle beam is an electron beam.

34. The method of claim 29 wherein the charged particle beam is an ion beam.

35. The method of claim 29 wherein the angular deviation measurement is responsive to various inaccuracies.

36. The method of claim 29 wherein the rotational movement is of about 180 degrees.

37. The method of claim 29 wherein the measurements are performed at sidewall portions that are characterized by a small angular variation

38. A method for determining an angular deviation of a charged particle beam, the method comprising the steps of:

providing a test object that comprises a first and second substantially equal structural elements, each structural element includes multiple sidewalls;

measuring a feature of at least one sidewall of a first structural element;

changing a relationship between the charged particle beam and the test object;

measuring a feature of at least one sidewall of the second structural element; and

processing the measurements to determine the angular deviation of the charged particle beam.

39. The method of claim 38 wherein the measurements are performed at sidewall portions that are characterized by a small angular variation.

40. A method for calibrating a charged particle beam system, the method comprising the steps of:

setting a charged particle beam to a certain tilt state;

determining calibrated beam control parameters values;

changing the certain tilt state and repeating the step of determining a calibrated beam control parameters.

41. The method of claim 40 wherein the step of determining calibrated beam control parameters comprises determining a relationship between angular deviation and beam control parameters values.

42. The method of claim 40 wherein the charged particle beam system is capable of being operated at multiple tilt states and wherein the steps of setting, determining and changing are repeated for at least two tilt states.

43. The method of claim 42 wherein calibrated beam control parameters values associated with a certain tilt state are used during calibrating the charged particle beam system during another tilt state.

44. The method of claim 40 wherein the charged particle beam is an electron beam.

45. The method of claim 40 wherein the charged particle beam is an ion beam.

46. The method of claim 40 wherein the angular deviation measurement is responsive to various inaccuracies.

47. The method of claim 40 wherein the step of determining calibrated beam control parameters values comprises measuring an angular deviation.

48. The method of claim 47 wherein measuring an angular deviation comprises the steps of: providing a test object that comprises a structural element that has multiple sidewalls; measuring a feature of at least one sidewall of the structural element; changing the relationship between the charged particle beam and the test object; measuring a feature of at least one sidewall of the structural element; and processing the measurements to determine the angular deviation of the charged particle beam.

49. The method of claim 48 wherein measuring an angular deviation comprises the steps of: providing a test object that comprises a structural element that has multiple sidewalls; measuring a feature of at least one sidewall of the structural element; introducing a rotational movement between the charged particle beam and the test object; measuring a feature of at least one sidewall of the structural element; and processing the measurements to determine the angular deviation of the charged particle beam.

50. The method of claim 48 wherein the measurements are performed at sidewall portions that are characterized by a small angular variation.

51. A method for determining an angular deviation of a charged particle beam, the method comprising the steps of:

providing a test object that comprises a first and a second structural elements that are oriented towards each other by a first planar angle $\alpha 1$; whereas the first structural element has a first sidewall that is oriented at a first sidewall angle $\beta 1$; whereas the second structural element had a second sidewall that is oriented at a second sidewall angle $\beta 2$;

measuring a feature of the first sidewall by scanning the first sidewall with a charged particle beam whereas the angular orientation between the charged particle beam and the first sidewall is greater than $\beta 1$;

measuring a feature of the second sidewall by scanning the second sidewall with a charged particle beam whereas the angular orientation between the charged particle beam and the second sidewall is greater than $\beta 2$;

measuring a feature of the first sidewall by scanning the first sidewall with a charged particle beam whereas the angular orientation between the charged particle beam and the first sidewall is smaller than $\beta 1$;

measuring a feature of the second sidewall by scanning the first sidewall with an charged particle beam whereas the angular orientation between the charged particle beam and the second sidewall is smaller than $\beta 2$; and

determining the angular deviation in response to the measurements.

52. The method of claim 51 further comprising a step of determining beam control parameters in response to the angular deviation.

53. The method of claim 52 wherein the beam control parameters values comprise a combination of deflectors current and voltage values.

54. The method of claim 52 wherein the beam control parameters values are calculated for different charged particle beam tilt states.

55. The method of step 52 further comprising calibrating charged particle beam deflectors in response to at least one beam control parameter.

56. A system for determining an angular deviation of a charged particle beam, the system comprising:

means for performing at least two measurements of a feature of a structural element of a test object whereas each measurement involves an interaction between the test object and a charged particle beam; and whereas the measurements differ from each other by a relationship between a charged particle beam and the test structure; and

means for processing the at least two measurements for determining the angular deviation.

57. The system of claim 56 whereas the means for performing comprises means for controlling the charged electron beam and detection unit for measuring particles resulting from the interaction.

58. The system of claim 56 further comprising a stage for changing the relationship by introducing a relative movement between the test structure and the electron beam.

59. The system of claim 56 wherein the relative movement is a relative rotation.

60. The method of claim 59 wherein the relative rotation is about 180 degrees.

61. The system of claim 56 further adapted to determine calibrated beam control parameters values in response to at least one measured angular deviation.

62. The system of claim 56 wherein the measured feature is a width of a sidewall of the structural element.

63. The system of claim 56 further adapted to determining beam control parameters values in response to the angular deviation.

64. The system of claim 56 capable of positioning the charged particle beam in multiple tilt states, and whereas the system is capable of determining the deviation angle of the charged particle beam for at least two tilt states.

65. The system of claim 56 wherein the charged particle beam is an electron beam.

66. The system of claim 56 wherein the charged particle beam is an ion beam.

67. The method of claim 56 wherein the angular deviation measurement is responsive to various inaccuracies.

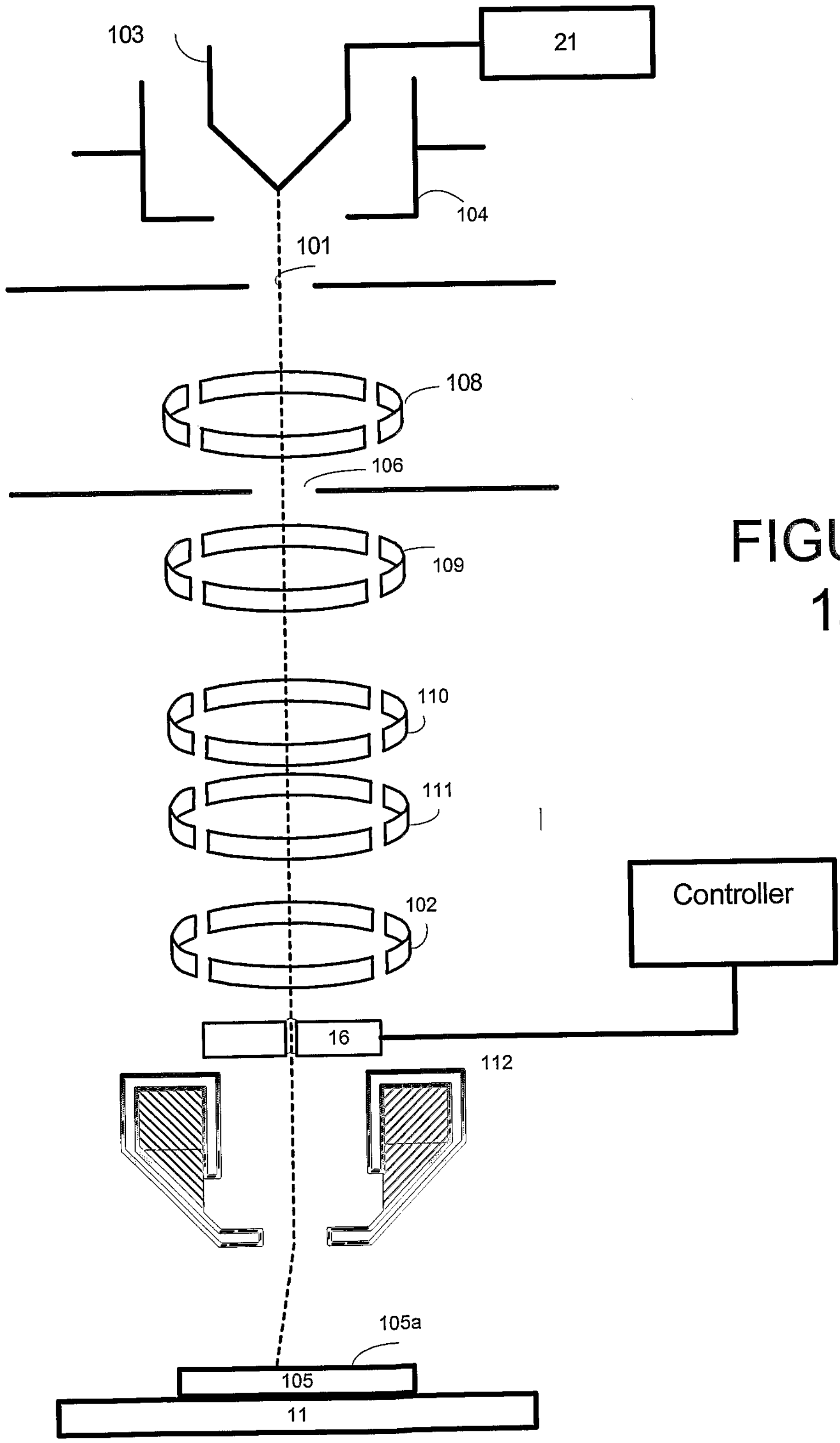

103
21
104
101
108
106
109
110
111
102
Controller
16
112
105a
105
11

FIGURE 1a

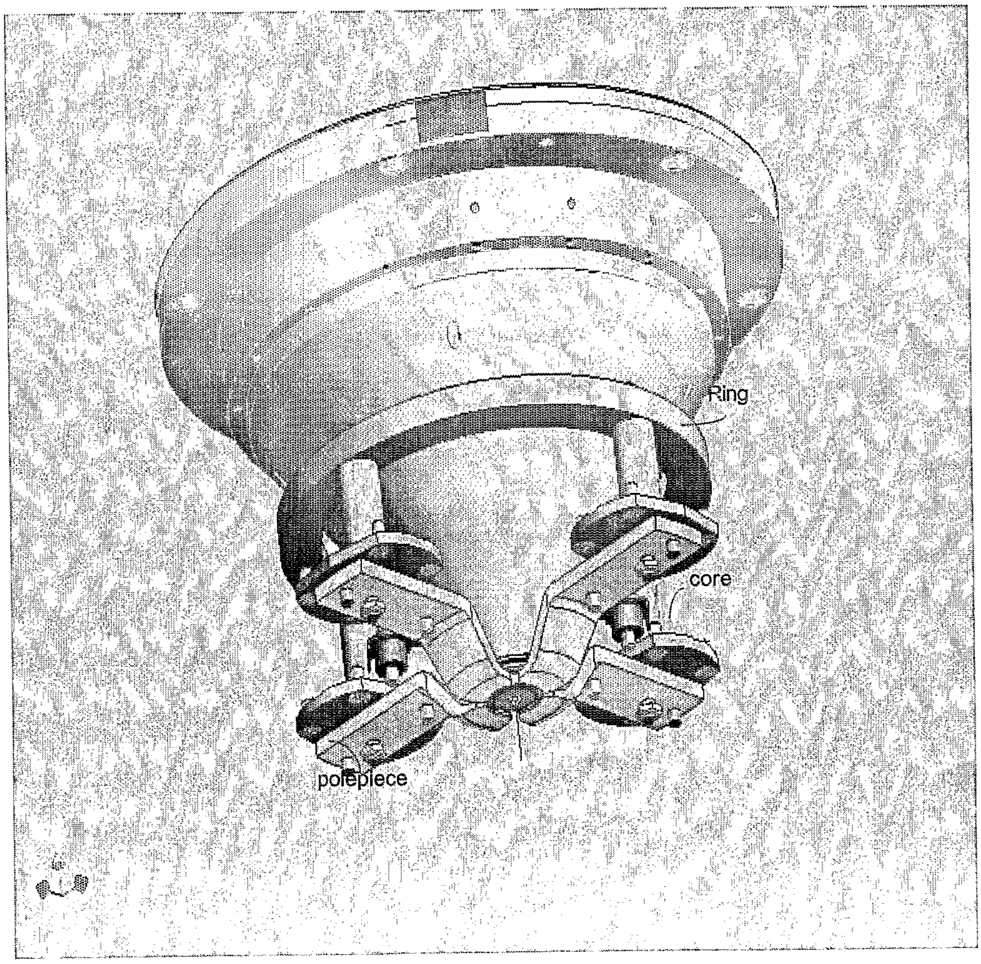
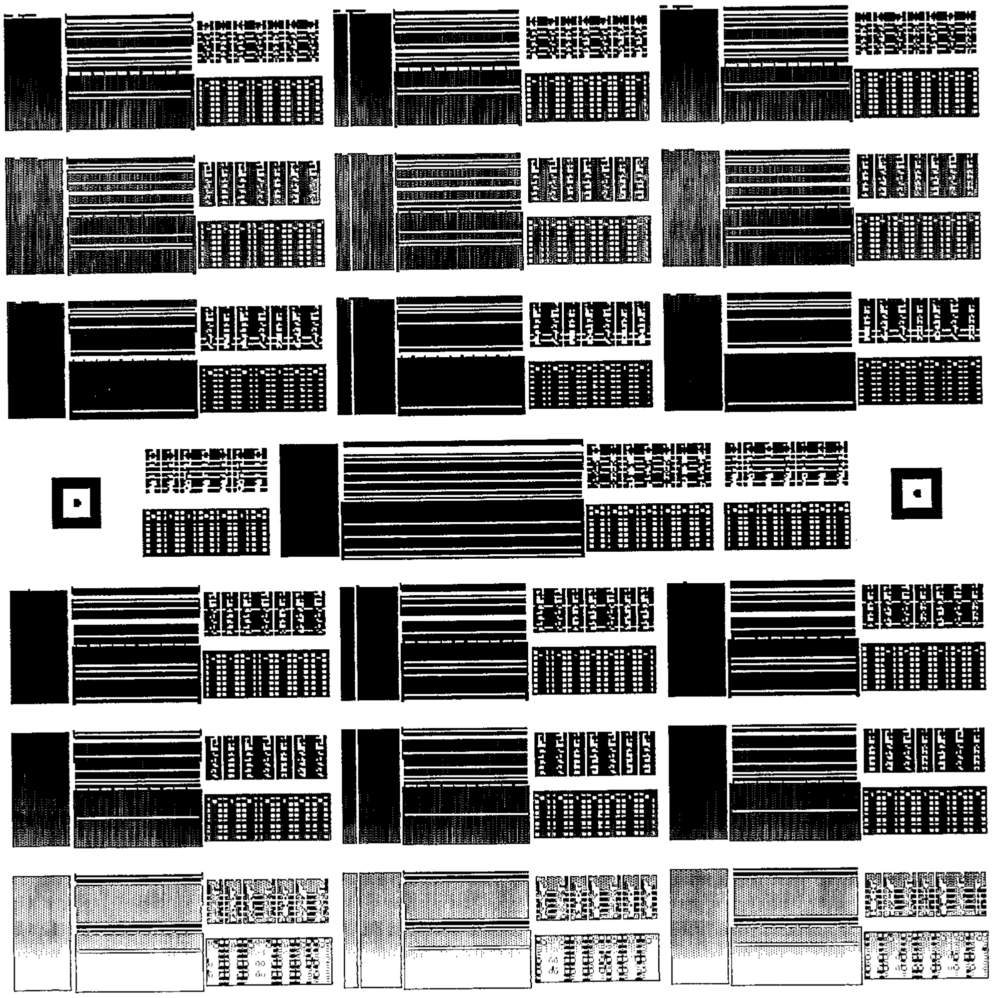



FIGURE 1b

# FIGURE 2



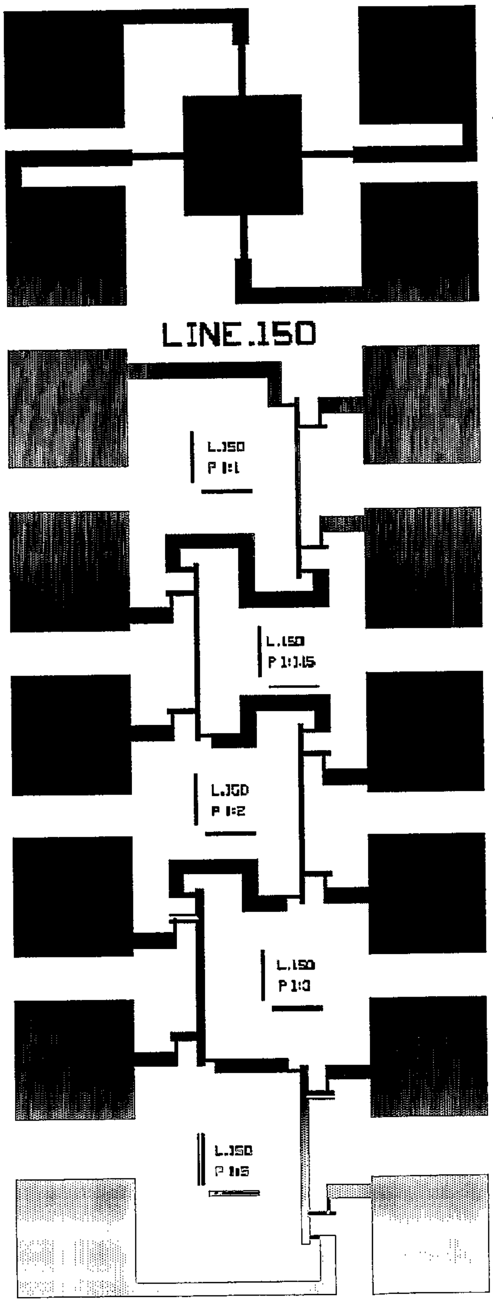



FIGURE 3

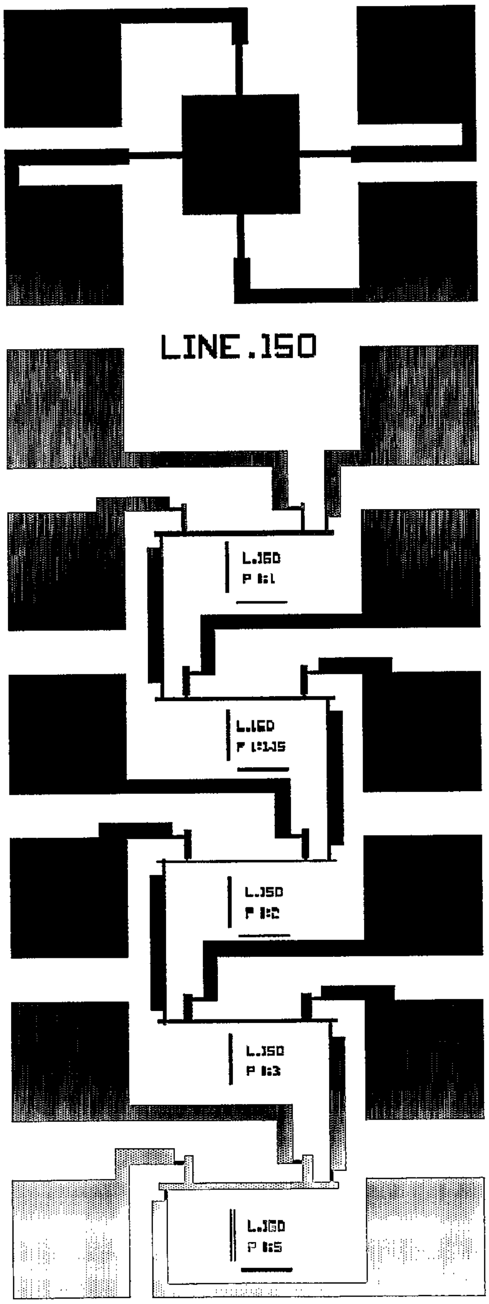



FIGURE 4

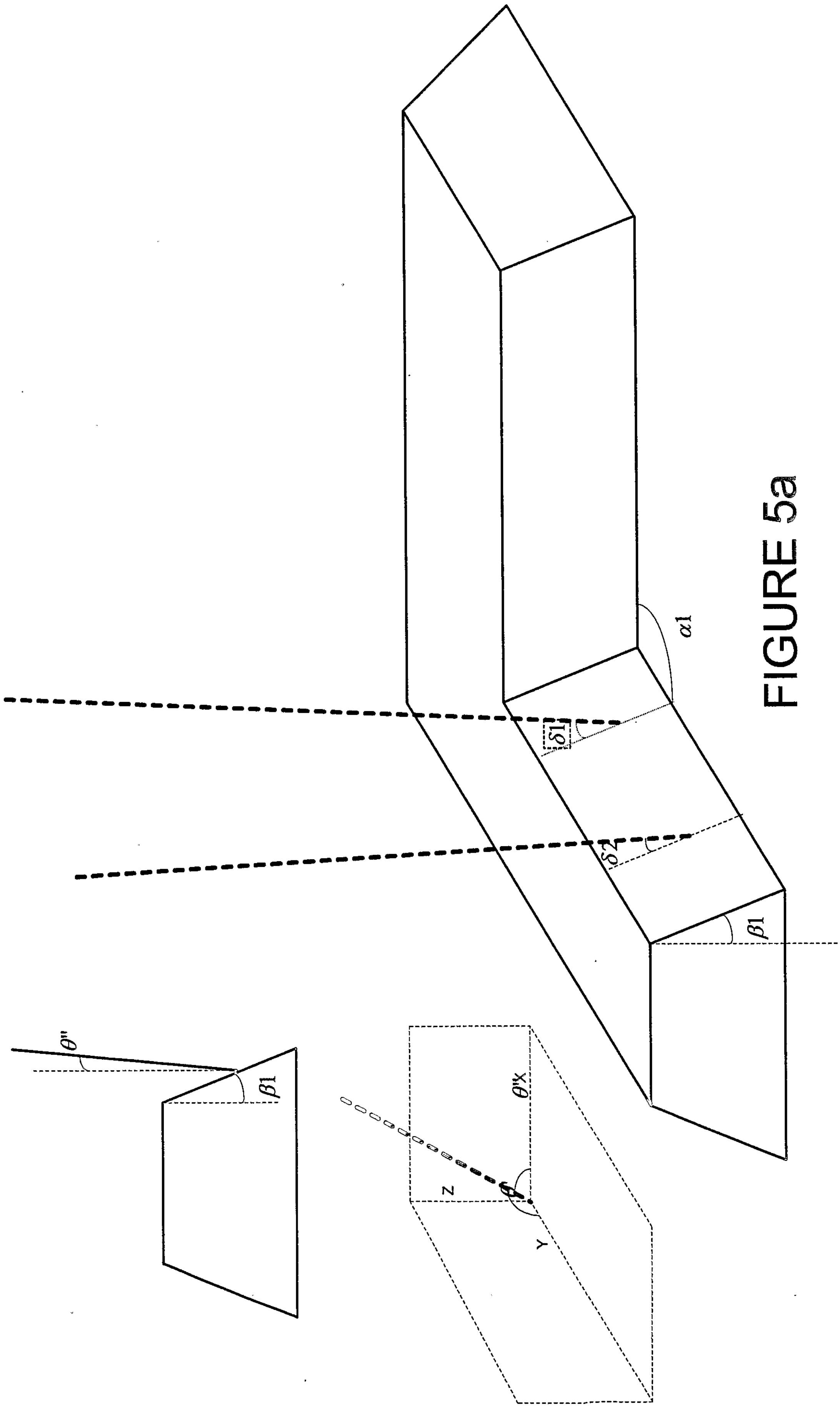



FIGURE 5a

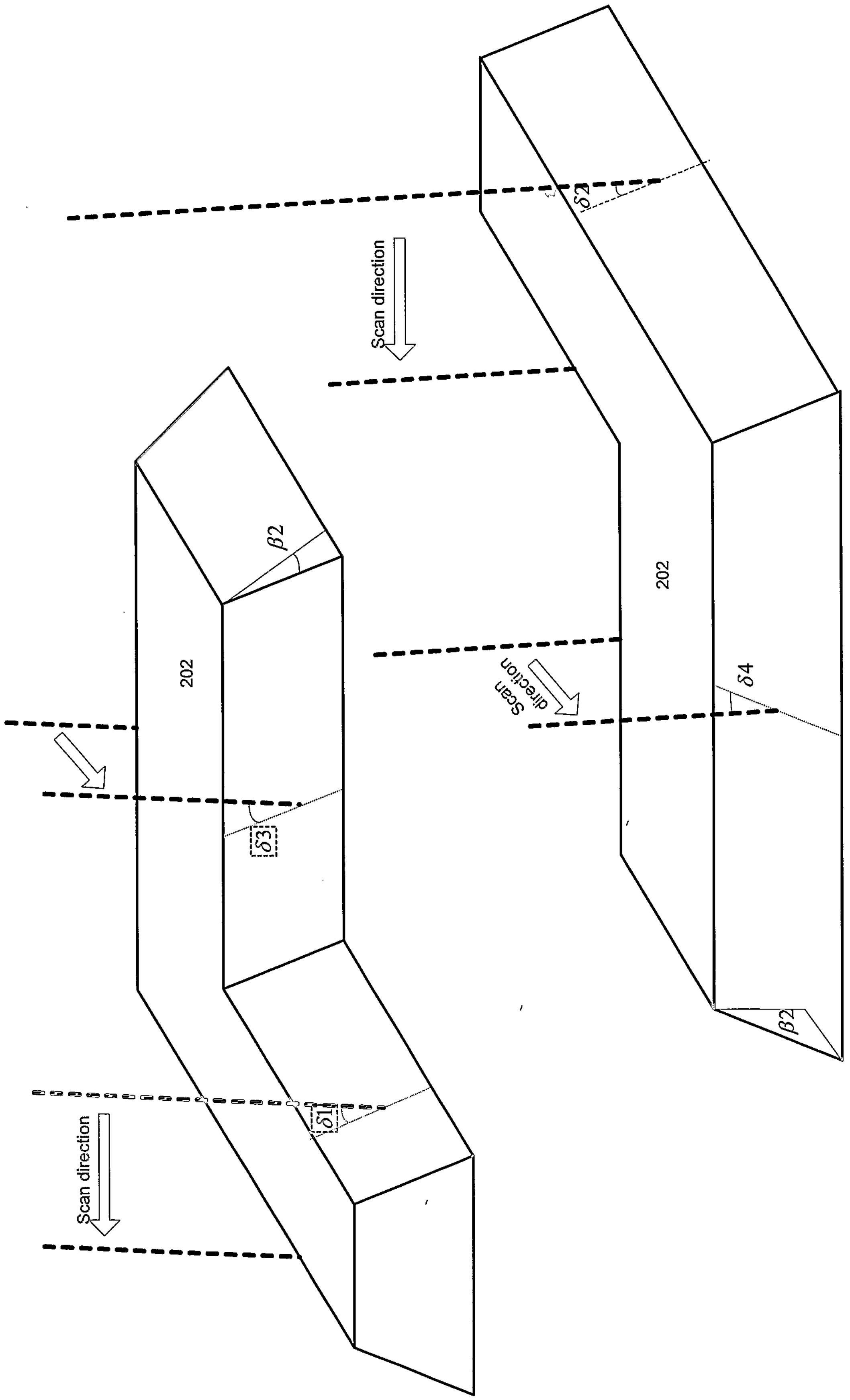
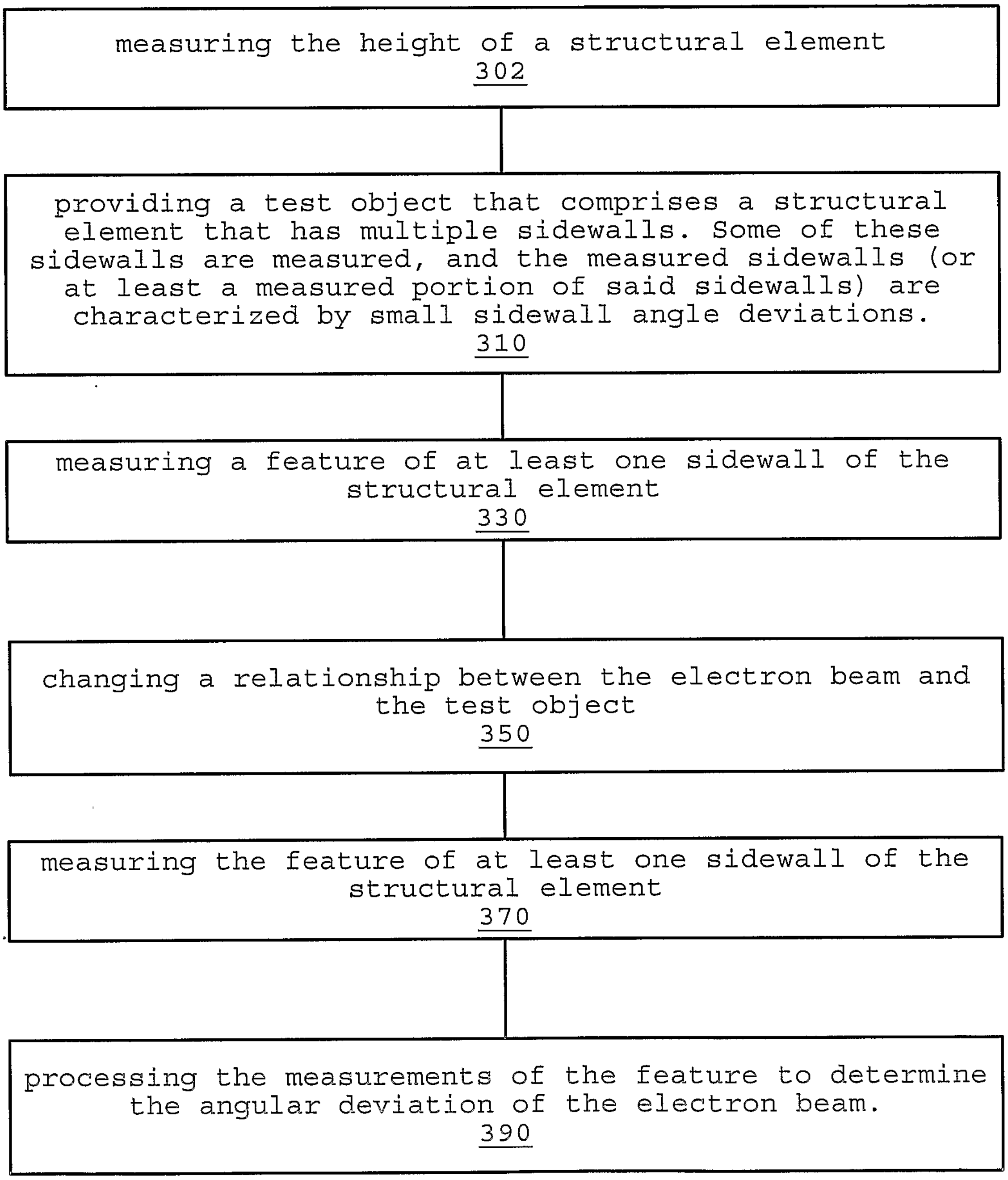

Scan direction
Scan direction
Scan direction
202
202
β2
β2
δ1
δ2
δ3
δ4

FIGURE 5b


measuring the height of a structural element
302
providing a test object that comprises a structural element that has multiple sidewalls. Some of these sidewalls are measured, and the measured sidewalls (or at least a measured portion of said sidewalls) are characterized by small sidewall angle deviations.
310
measuring a feature of at least one sidewall of the structural element
330
changing a relationship between the electron beam and the test object
350
measuring the feature of at least one sidewall of the structural element
370
processing the measurements of the feature to determine the angular deviation of the electron beam.
390

300

FIGURE 6

providing a test object that includes a first and a second structural elements; whereas the first structural element has a first sidewall that is oriented at a first sidewall angle $\beta 1$; whereas the second structural element had a second sidewall that is oriented at a second sidewall angle $\beta 2$
410

measuring a feature of the first sidewall by scanning the first sidewall with an electron beam whereas the angular orientation between the electron beam and the first sidewall is greater than $\beta 1$
430

measuring a feature of the second sidewall by scanning the second sidewall with an electron beam whereas the angular orientation between the electron beam and the second sidewall is greater than $\beta 2$
450

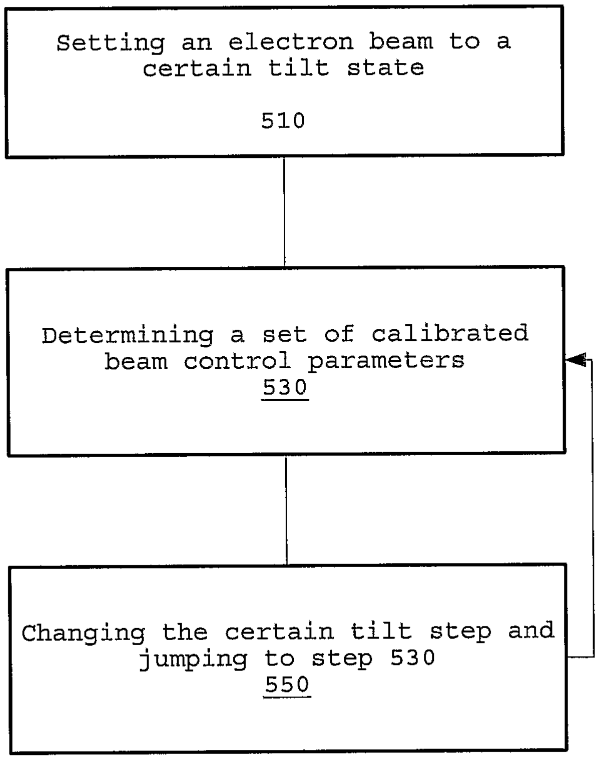
measuring a feature of the first sidewall by scanning the first sidewall with an electron beam whereas the angular orientation between the electron beam and the first sidewall is smaller than $\beta 1$
470

measuring a feature of the second sidewall by scanning the first sidewall with an electron beam whereas the angular orientation between the electron beam and the second sidewall is smaller than $\beta 2$
490

determining the angular deviation in response to the measurements
495

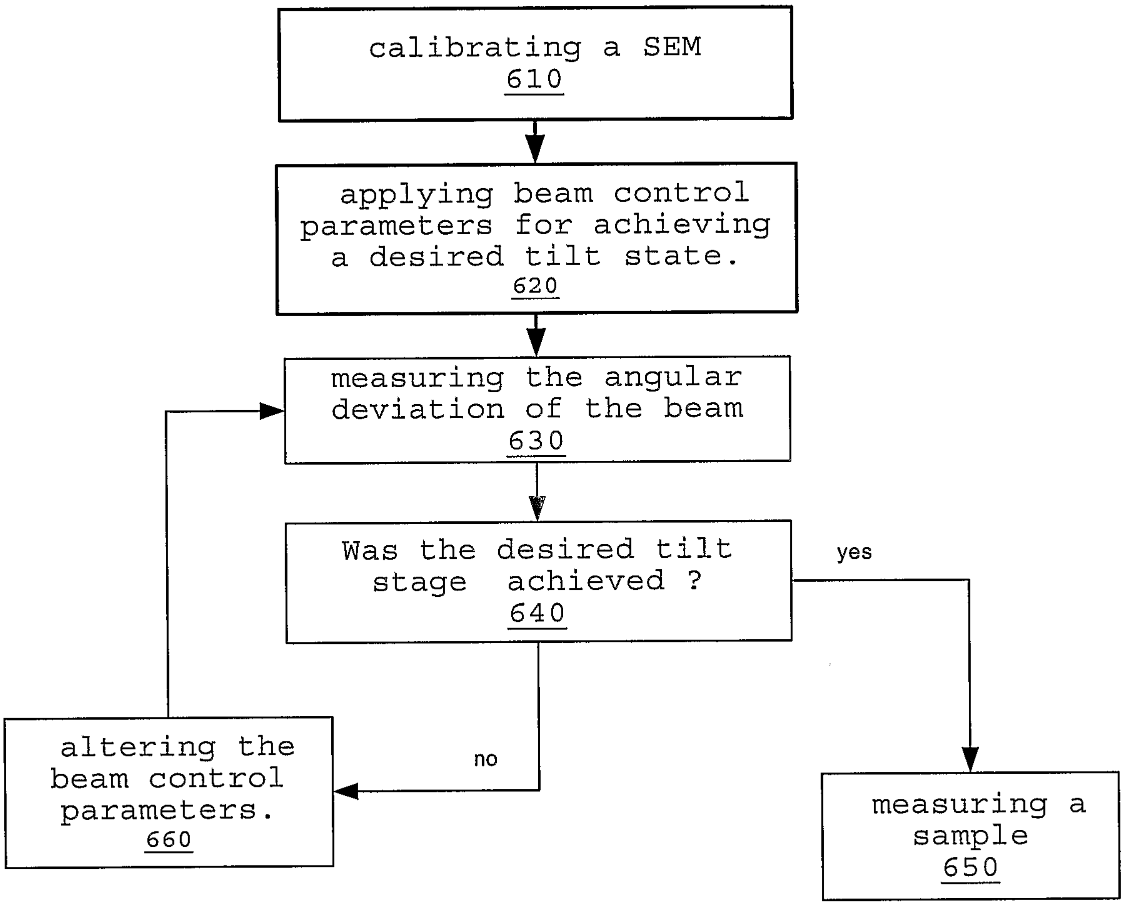
400

FIGURE 7


Setting an electron beam to a certain tilt state
510
Determining a set of calibrated beam control parameters
530
Changing the certain tilt step and jumping to step 530
550

500

FIGURE 8


calibrating a SEM
610
applying beam control parameters for achieving a desired tilt state.
620
measuring the angular deviation of the beam
630
Was the desired tilt stage achieved ?
640
yes
no
altering the beam control parameters.
660
measuring a sample
650

600

FIGURE 9

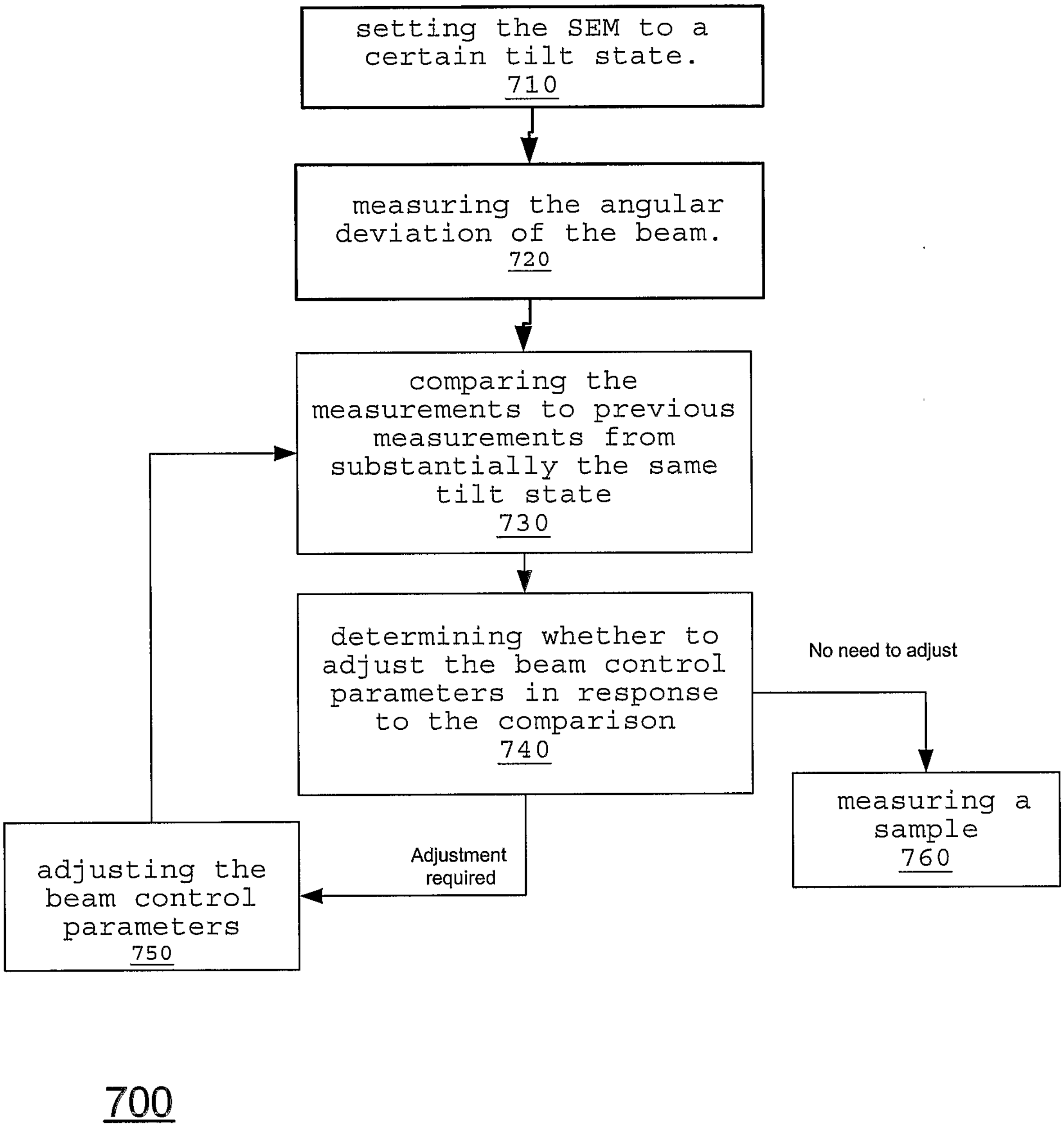

setting the SEM to a certain tilt state. 710
measuring the angular deviation of the beam. 720
comparing the measurements to previous measurements from substantially the same tilt state 730
determining whether to adjust the beam control parameters in response to the comparison 740
No need to adjust
measuring a sample 760
Adjustment required
adjusting the beam control parameters 750
700

FIGURE 10