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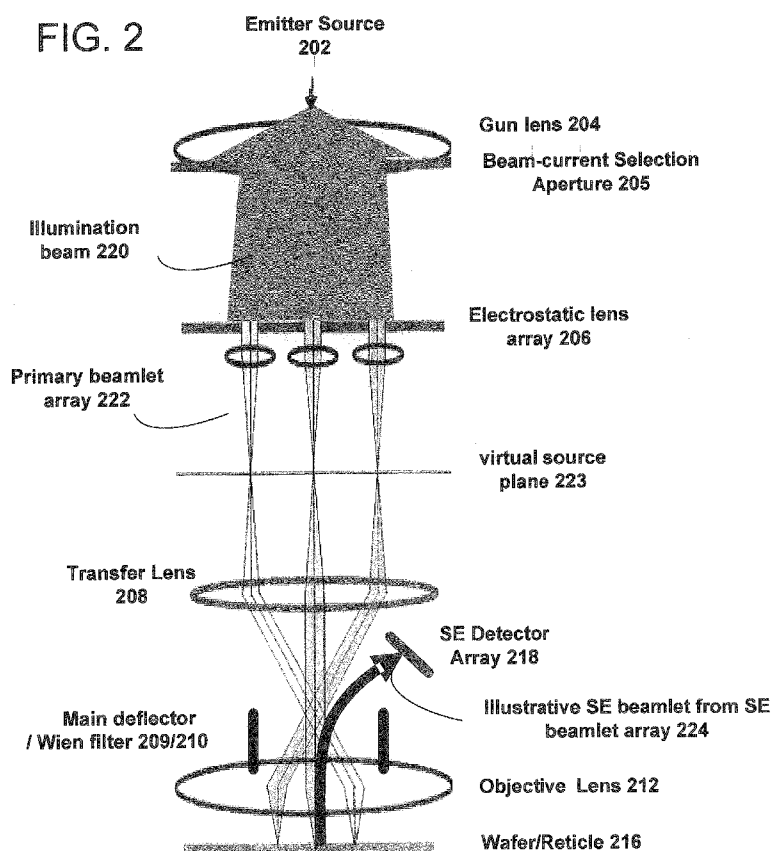
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[Continued on next page]

(54) Title: MULTIPLE-BEAM SYSTEM FOR HIGH-SPEED ELECTRON-BEAM INSPECTION

FIG. 2



(57) Abstract: One embodiment disclosed relates to a multiple-beamlet electron beam imaging apparatus for imaging a surface of a target substrate. A beam splitter lens array is configured to split the illumination beam to form a primary beamlet array, and a scanning system is configured to scan the primary beamlet array over an area of the surface of the target substrate. In addition, a detection system configured to detect individual secondary electron beamlets. Another embodiment disclosed relates to a method of imaging a surface of a target substrate using a multiple-beamlet electron beam column. Other features and embodiments are also disclosed.



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## **MULTIPLE-BEAM SYSTEM FOR HIGH-SPEED ELECTRON-BEAM INSPECTION**

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### **CROSS-REFERENCE TO RELATED APPLICATION(S)**

The present application claims the benefit of US. Provisional  
Application No. 61/466,466, filed on March 23, 2011, entitled "Multiple-Beam  
10    System for High-Speed E-Beam Inspection," the disclosure of which is hereby  
incorporated by reference.

### **BACKGROUND**

#### *15    Technical Field*

The present invention relates to apparatus and methods for  
automated inspection of manufactured substrates.

#### *Description of the Background Art*

20                      Automated electron beam inspection systems typically use an  
electron beam column to scan an electron beam across a region of a substrate  
surface to obtain image data. The image data may be processed to detect  
manufacturing defects in the region.

#### **25                      BRIEF DESCRIPTION OF THE DRAWINGS**

FIG. 1 is a cross-sectional diagram depicting electron-optics of a  
multi-beam electron beam column for an automated inspection system in  
accordance with an embodiment of the invention.

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FIG. 2 is a cross-sectional diagram of a first configuration of select electron-optical components in accordance with an embodiment of the invention.

FIG. 3 is a cross-sectional diagram of a second configuration of select electron-optical components in accordance with an embodiment of the invention.

FIGS. 4A and 4B are cross-sectional diagrams which illustrate switchability between multi-beam and single-beam operational modes in accordance with an embodiment of the invention.

FIG. 5 is a graph showing beam current improvement which is achieved in accordance with an embodiment of the invention.

FIG. 6A is a cross-sectional diagram depicting an implementation of a multi-beam electron beam column for an automated inspection system in accordance with an embodiment of the invention.

FIG. 6B is a cross-sectional diagram showing a beam splitter electrostatic lens array stack in accordance with an embodiment of the invention.

FIG. 6C is a plan view diagram showing a beam splitter electrostatic lens array stack in accordance with an embodiment of the invention.

FIG. 7A is a cross-sectional diagram showing computer-simulated primary beam trajectories through the lenses of the multi-beam column in accordance with an embodiment of the invention.

FIG. 7B shows a close-up view of the computer-simulated primary electron trajectories as they impinge upon the surface of a wafer in accordance with an embodiment of the invention.

FIG. 8 is a plan view of a detector cell array in accordance with an embodiment of the invention.

FIG. 9A is a schematic diagram depicting a frame image mode for beamlet scanning in accordance with an embodiment of the invention.

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FIG. 9B is a schematic diagram depicting a swathing image mode for beamlet scanning in accordance with an embodiment of the invention.

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## SUMMARY

One embodiment disclosed relates to a multiple-beamlet electron beam imaging apparatus for imaging a surface of a target substrate. A beam splitter lens array is configured to split the illumination beam to form a primary beamlet array, and a scanning system is configured to scan the primary beamlet array over an area of the surface of the target substrate. In addition, a detection system configured to detect individual secondary electron beamlets. Another embodiment disclosed relates to a method of imaging a surface of a target substrate using a multiple-beamlet electron beam column. Other embodiments, aspects and feature are also disclosed.

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## DETAILED DESCRIPTION

Conventional systems for wafer and reticle inspection raster scan a single beam over a sample area and obtain image data pixel by pixel. This results in a very slow speed (low throughput) for conventional inspection systems.

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In contrast to conventional systems, the present disclosure provides a novel and inventive multiple-beam system for use in automated electron beam inspection and other applications. The system, apparatus, and methods disclosed herein may be advantageously applied, for example, to defect inspection of semiconductor wafers, reticles, photo masks, EUV masks, and other manufactured substrates.

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FIG. 1 is a cross-sectional diagram depicting electron-optics of a multi-beam electron beam (e-beam) column **100** for an automated inspection system in accordance with an embodiment of the invention. The multi-beam e-beam column **100** shown in FIG. 1 produces multiple beamlets from a single  
5 electron emitter and shares column optical elements by the beamlets. As depicted, the multi-beam electron beam column **100** includes an emitter source **102**, illumination electron-optics (illumination optics) **104**, a beam splitter lens array **106**, transfer electron-optics (transfer optics) **108**, main deflectors **109** with an ExB Wien filter **110**, electrostatic and/or magnetic objective optics **112**, charge  
10 control electrode **114**, a sample (wafer or reticle) **116** being imaged, and secondary electron detection electron-optics (SE detection optics) **117** and a detector system **118**.

The emitter source **102** may be implemented as a Schottky tip and is configured to emit electrons for the illumination beam **120**. The illumination  
15 optics **104** may be configured to provide focus adjustment prior to the illumination beam **120** impinging upon the beam splitter lens array **106**.

Multiple beamlets in a primary beamlet array **122** are formed by the electrons of the illumination beam **120** passing through the beam splitter lens array **106**. For example, the primary beamlet array **122** may comprise twenty-five  
20 beamlets in a 5x5 array. More generally, it is contemplated that the number of beamlets in the primary beamlet array **122** may range from two to two hundred (2 to 200). Each beamlet in the primary beamlet array **122** has its own separate virtual source. The primary beamlet array **122** is further focused by the transfer and objective optics (**108** and **112**) to multiple beamlet spots on the surface of the  
25 sample **116**. The build-up of charge on the surface of the sample **116** may be controlled using the charge control electrode **114**.

The main deflectors **109** may be configured to scan the primary beamlet array **122** over an area of the sample **116**. Each beamlet spot on the

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surface of the sample **116** generates a corresponding secondary electron (SE) beamlet. An array of SE beamlets **124** is generated due to the impingement of the primary beamlet array **122** onto the surface of the sample **116**. In FIG. 1, one illustrative SE beamlet of the array of SE beamlets **124** is shown.

5               The ExB Wien filter **110** may be configured to separate the SE beamlet array **124** from the primary beamlet array **122** by bending the upwards trajectories of the SE beamlets towards the SE detection optics **117** (while not bending the downwards trajectories of the primary beamlets). The SE detection optics **117** may be configured to focus each SE beamlet onto a detector element  
10 of the detector system **118**. As such, signal electrons from each SE beamlet in the array **124** may be detected in parallel by multiple detector elements in the detector system **118**.

FIG. 2 is a cross-sectional diagram of a first configuration **200** of select electron-optical components in accordance with an embodiment of the  
15 invention. Components shown in FIG. 2 include an emitter source **202**, a gun lens **204**, a beam-current selection aperture **205**, an electrostatic lens array **206**, transfer lens **208**, main deflector **209** / Wien filter **210**, objective lens **212**, a substrate (wafer or reticle) **216** being imaged, and secondary electron (SE) detector array **218**.

20               As shown, the illumination system includes an emitter source **202**, a gun lens **204**, and a beam-current selection aperture **205**. The emitter source **202** emits electrons which are focused by the gun lens **204** and limited by the beam-current selection aperture **205** so as to generate the illumination beam **220**.

Multiple beamlets in a primary beamlet array **222** are formed by the  
25 electrons of the illumination beam **220** passing through the electrostatic lens array **206**. For example, the primary beamlet array **222** may comprise nine beamlets in a 3x3 array. More generally, it is contemplated that the number of beamlets in the primary beamlet array **222** may range from two to two hundred (2

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to 200). Each beamlet in the primary beamlet array **222** has its own separate virtual source located on the virtual source plane **223**. The primary beamlet array **222** is further focused by the transfer and objective optics (**208** and **212**) to multiple beamlet spots on the surface of the sample **216**.

5               The main deflector **209** may be configured to scan the primary beamlet array **222** over an area of the sample **216**. Each beamlet spot on the surface of the sample **216** generates a corresponding secondary electron (SE) beamlet. An array of SE beamlets **224** is generated due to the impingement of the primary beamlet array **222** onto the surface of the sample **216**. In FIG. 1, one  
10 illustrative SE beamlet of the array of SE beamlets **224** is shown.

              The ExB Wien filter **210** may be configured to separate the SE beamlet array **224** from the primary beamlet array **222** by bending the upwards trajectories of the SE beamlets towards the SE detector array **218** (while not bending the downwards trajectories of the primary beamlets). In the  
15 configuration depicted in FIG. 2, the SE detector array **218** is positioned just following the Wien filter **210**. This detection arrangement is advantageously compact.

              FIG. 3 is a cross-sectional diagram of a second configuration **300** of select electron-optical components in accordance with an embodiment of the  
20 invention. This configuration **300** has a different detection arrangement compared to the first configuration **200** of FIG. 2.

              In the detection arrangement shown in FIG. 3, the SE beamlet array **224** is bent further away from the primary beamlet array **222** using an SE bender **302**. This provides space for additional electron-optical components to adjust the  
25 SE beamlet array **224** prior to the SE beamlet array **224** reaching the SE detector array **310**. For example, the additional components may include, in series, a variable focus adjustment electron lens (focus adjust) **304**, a variable rotation adjustment electron lens (rotation adjust) **306**, and a variable magnification

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adjustment electron lens (mag adjust) **308**. Advantageously, this detection arrangement may provide superior multi-beam imaging detection quality and flexibility.

FIGS. 4A and 4B are cross-sectional diagrams which illustrate switchability between multi-beam and single-beam operational modes in a single electron beam column in accordance with an embodiment of the invention. FIG. 4A shows the electron-optics of a multi-beam e-beam column when it is operating in a multi-beam mode **400A**, while FIG. 4B shows the electron-optics of a multi-beam e-beam column when it is operating in a single-beam mode **400B**.

In FIG. 4A, the switchable beam splitter lens array **406A** is in place such that the illumination beam **120** is split into a primary beamlet array **422A**. In addition, the transfer optics is turned on **412A** to support the multi-beam mode. As such, the primary beamlet array **422A** impinges upon an array of spots on the surface of the sample **116** and results in the secondary electron beamlet array **424A** which is detected by the SE detection optics and system (**117** and **118**).

In FIG. 4B, one of a plurality of beam-current (BC) selection apertures **406B** are switched into place (replacing the beam splitter lens array **406A**). This results in a primary single beam **422B** (instead of a primary beamlet array **422A**). In addition, the transfer optics is turned off **412B** to allow the primary single beam **422B** to pass through. Hence, the primary single beam **422B** impinges upon a single spot on the surface of the sample **116** and results in the single secondary electron (SE) beam **424B** (instead of the SE beamlet array **424A**) which is detected by the SE detection optics and system (**117** and **118**).

FIG. 5 is a graph showing beam current improvement which is achieved in accordance with an embodiment of the invention. The graph shows beam spot size (in log scale) on the vertical axis and total beam current (in log scale) on the horizontal axis. Computed curves from electron-optical simulations

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are shown for a single beam system **502** and for a system with 25 beamlets in a 5x5 array **504**. For the same spot size (i.e. for the same resolution capability), the 5x5 beamlet system is shown to provide a total beam current which is more than ten times (10x) and up to about twenty-five (25x) times that of the single beam system.

FIG. 6A is a cross-sectional diagram depicting an implementation of a multi-beam electron beam column **600** for an automated inspection system in accordance with an embodiment of the invention. As shown, the multi-beam electron beam column **600** includes a Schottky emitter module **602**, a gun magnetic condenser lens **604**, a beam-current selection aperture (BSA) **605**, a beam splitter electrostatic lens array stack **606**, pre-scanner deflector **607**, a three-electrode electrostatic transfer lens **608**, main scanner deflector/Wien filter **609/610**, an electro-magnetic objective optics **612**, charge control electrode **614**, and a sample (wafer or reticle) **616** being imaged.

In this implementation, the gun magnetic condenser lens may be an immersion magnetic condenser lens which may be configured to adjust the beam current density to illuminate the beam splitter. The beamlets in the primary beamlet array may be focused by the transfer lens to a common crossover at, or close to, the back-focal plane of the final objective lens. The electro-magnetic objective lens may be configured to focus the individual beamlets into individual spots on the sample surface. The primary beamlet array may be scanned over the sample surface using a scanning system which includes both the pre-scanner and the main scanner.

In addition, the multi-beam electron beam column **600** includes a spherical electrostatic bender **632** with a higher voltage (+V) on an inner spherical component so as to bend the secondary electron (SE) beamlet array to the SE beam aligner **634**. The SE beam aligner **634** aligns the SE beamlet array so that the beamlets are properly aligned as they enter the SE adjustment optics

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**636.** The SE adjustment optics **636** may be configured to adjust the focus, rotation, and magnification of the SE beamlet array so that the SE beamlets may be individually detected by cells or segments of the detector **638**.

FIGS. 6B and 6C show, respectively, cross-section and plan views of a beam splitter electrostatic lens array stack **606** in further detail in accordance with an embodiment of the invention. The stack may include alternating electrically-grounded (gnd) electrode plates **642** and electrically-floating (float) electrode plates **644**. In the illustrated example, there are seven plates, four grounded and three floating, with grounded plates being at the top and bottom of the stack. In this case, each electrostatic lens in the lens array may be considered to include three sets of three-electrode Enzel lenses. As contemplated herein, in other examples, the stack may have a different number of electrode plates.

The electrode plates are perforated with beamlet-forming columnar openings **654** which are aligned from plate to plate so as to extend through the stack. Each opening is surrounded by an electron-blocking electrode area **652**. In the illustrated example, the openings form a 7x7 array so as to form a 7x7 array of primary beamlets. As contemplated herein, in other examples, the openings may be arranged so as to form other arrays beamlets (with the number of beamlets ranging from two to two hundred). A center such opening may be aligned with the optical axis (OA) of the electron beam column.

FIG. 7A is a cross-sectional diagram showing computer-simulated primary beam trajectories through the lenses of the multi-beam column in accordance with an embodiment of the invention. As shown, the lenses include the gun lens **704**, the beam splitter lenses **706**, the transfer lens **708**, and the objective lens **712**. FIG. 7B shows a close-up view of the computer-simulated primary electron trajectories as they impinge upon the surface of the wafer **716** in accordance with an embodiment of the invention. As sheen, the landing angle of

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the electrons is normal to the surface of the wafer. In other words, the primary electron beam has a telecentric landing at the target surface.

FIG. 8 is a plan view of a detector cell array in accordance with an embodiment of the invention. As shown, the detector may include an array of detector cells, and each cell may detect a separate secondary electron (SE) beamlet.

While the illustrated example of a detector cell array in FIG. 8 shows nine detector cells in a 3x3 array, the number of cells in the detector array will depend on the particular implementation. In one embodiment, the number of cells in the detector array may correspond to the number of beamlets in the SE beamlet array to be detected. For example, if there are 25 SE beamlets in a 5x5 array, then there may be 25 detector cells in a 5x5 array to detect those SE beamlets.

As shown in FIGS. 9A and 9B, the beamlets of the primary beamlet array may be scanned simultaneously over individual regions of the sample surface. FIG. 9A is a schematic diagram depicting a frame image mode for beamlet scanning in accordance with an embodiment of the invention, while FIG. 9B is a schematic diagram depicting a swathing image mode for beamlet scanning in accordance with an embodiment of the invention.

In FIG. 9A, the sample may be stationary while the beamlets are scanned. Each beamlet may be scanned in a raster pattern such that it covers its own sub-area of the framed surface area to be scanned. For example, each beamlet may be controlled by a slower frame scan signal in the X-direction and a faster line scan signal in the Y-direction, where the period of the frame scan signal is multiple times longer than the period of the line scan signal. In this way, the entire framed surface area to be scanned may be imaged by the beamlet array.

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In FIG. 9B, the sample is moving while the beamlets are scanned. In the example shown, the stage holding the sample is moving in a linear motion to the left in the X-direction. Meanwhile, each beamlet may be scanned using a line scan signal in the Y-direction. In this way, each beamlet may covers its own  
5 sub-area of the framed surface area to be scanned. Note that, while a two-dimensional array of beamlets may be used for swath scanning as shown in FIG. 9B, an alternative implementation may use a one-dimensional array of beamlets for swath scanning (where the array of beamlets would extend along the Y-dimension in the figure).

10 While the illustrated example of a primary beamlet array in FIGS. 9A and 9B show nine beamlets in a 3x3 array, the number of beamlets in the primary beamlet array will depend on the particular implementation. In one embodiment, the number of beamlets in the primary beamlet array may correspond to the number of cells in the detector array. For example, if there are  
15 25 detector cells in a 5x5 array to detect SE beamlets, then there may be 25 primary beamlets in a 5x5 array.

### *Conclusion*

The throughput of electron beam inspection systems is mainly  
20 limited by the electron-optics and the scanning/imaging strategy. The electron-optics determines the trade off between resolution (related to sensitivity) and beam current (related to speed), where the maximum allowed beam current at certain resolution is limited by lens aberrations, source brightness and electron-electron interactions.

25 The conventional electron-beam inspection optics is based on a single beam approach. Given the shortest column length, the highest beam energy and the brightest source that can be practically achieved by the state-of-the-art technology, the single-beam based approaches are always constrained to

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the beam current range that is several orders of magnitude lower than what is required for the high throughput inspection in the semiconductor industry roadmap. For example, the roadmap may require greater than 0.1 wafer per hour throughput for less than 3x design rule layer inspection.

5                   There have been several proposed multi-column and multi-beam approaches attempting to achieve above goal; but none of them is successful so far either due to feasibility issues or an inadequate throughput boost. For example, those previous multi-column based approaches can only offer very limited extension versus a single-beam approach because a maximum of only  
10   about 5 to 10 columns can be effectively integrated together, so the throughput boost is less than 10x. Multi-beam (sharing the same column) approaches developed so far are too complicated to be feasible as practical inspection products. For example, most of them need individual beamlet control, deflection and focus, or require novel source technology which is far from mature. In  
15   contrast, the present disclosure provides a multi-beam approach that is feasible enough to be implemented as a reliable product within the roadmap required time frame.

                  The above-described diagrams are not necessarily to scale and are intended be illustrative and not limiting to a particular implementation. In the  
20   above description, numerous specific details are given to provide a thorough understanding of embodiments of the invention. However, the above description of illustrated embodiments of the invention is not intended to be exhaustive or to limit the invention to the precise forms disclosed. One skilled in the relevant art will recognize that the invention can be practiced without one or more of the  
25   specific details, or with other methods, components, etc. In other instances, well-known structures or operations are not shown or described in detail to avoid obscuring aspects of the invention. While specific embodiments of, and examples for, the invention are described herein for illustrative purposes, various equivalent

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modifications are possible within the scope of the invention, as those skilled in the relevant art will recognize.

These modifications can be made to the invention in light of the above detailed description. The terms used in the following claims should not be  
5 construed to limit the invention to the specific embodiments disclosed in the specification and the claims. Rather, the scope of the invention is to be determined by the following claims, which are to be construed in accordance with established doctrines of claim interpretation.

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## CLAIMS

What is claimed is:

1. A multiple-beamlet electron beam imaging apparatus for imaging a surface of a target substrate, the apparatus comprising:
  - an electron source configured to emit electrons;
  - a condensor electron lens configured to focus the emitted electrons from the electron source into an illumination beam;
  - a beam splitter lens array configured to split the illumination beam to form a primary beamlet array;
  - an objective electron lens configured to focus the primary beamlet array onto the surface of the target substrate so as to produce a secondary electron beamlet array;
  - a scanning system configured to scan the primary beamlet array over an area of the surface of the target substrate; and
  - a detection system configured to detect individual secondary electron beamlets of the secondary electron beamlet array.
2. The apparatus of claim 1, further comprising:
  - transfer electron-optics arranged between the beam splitter lens array and the objective electron lens.
3. The apparatus of claim 2, wherein the transfer electron-optics is configured to focus the primary beamlet array onto a back-focal plane of the objective electron lens.

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4. The apparatus of claim 2, wherein the scanning system includes a pre-scanner arranged above the transfer electron-optics and a main scanner arranged below the transfer electron-optics.

5. The apparatus of claim 1, wherein the detection system includes secondary electron adjustment optics.

6. The apparatus of claim 5, wherein the secondary electron adjustment optics includes a focus adjustment electron lens, a rotation adjustment electron lens, and a magnification adjustment electron lens.

7. The apparatus of claim 6, wherein the secondary electron adjustment optics further includes an array of detector cells.

8. The apparatus of claim 7, wherein the array of detector cells has a number of cells which is equal to a number of secondary electron beamlets in the secondary electron beamlet array.

9. The apparatus of claim 1, wherein the beam splitter lens array comprises an electrostatic lens array stack.

10. The apparatus of claim 9, wherein the electrostatic lens array stack comprises alternating electrically-grounded and electrically-floating electrode plates.

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11. The apparatus of claim 10, wherein said electrode plates are perforated with a plurality of beamlet-forming columnar openings which are aligned from plate to plate so as to extend through the electrostatic lens array stack.

12. The apparatus of claim 1, wherein the objective electron lens is configured to focus the primary beamlet array such that the primary beamlet array lands normal to the surface of the target substrate.

13. The apparatus of claim 1, wherein the scanning system is configured to scan each primary beamlet of the primary beamlet array in a raster pattern such that said primary beamlet covers a corresponding sub-area of a framed surface area.

14. The apparatus of claim 1, further comprising a translatable stage which holds the target substrate, wherein the scanning system is configured to scan each primary beamlet of the primary beamlet array in a first dimension while the target substrate is translated under the primary beamlet array in a second dimension which is perpendicular to the first dimension.

15. A method of imaging a surface of a target substrate using a multiple-beamlet electron beam column, the method comprising:

- emitting electrons into a vacuum chamber;
- focusing the emitted electrons from the electron source into an illumination beam;
- splitting the illumination beam to form a primary beamlet array;

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focusing the primary beamlet array onto the surface of the target substrate using an objective electron-lens so as to produce a secondary electron beamlet array;

scanning the primary beamlet array over an area of the surface of the target substrate; and

detecting individual secondary electron beamlets of the secondary electron beamlet array.

16. The method of claim 15, further comprising:

focusing the primary beamlet array onto a back-focal plane of the objective electron lens using transfer electron-optics.

17. The method of claim 15, further comprising adjusting the focus, rotation, and magnification of the secondary electron beamlet array prior to detecting the individual secondary electron beamlets.

18. The method of claim 15, wherein each primary beamlet of the primary beamlet array is scanned in a raster pattern such that said primary beamlet covers a corresponding sub-area of a framed surface area.

19. The method of claim 15, wherein each primary beamlet of the primary beamlet array is scanned in a first dimension while the target substrate is translated under the primary beamlet array in a second dimension which is perpendicular to the first dimension.

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20. An automated inspection system for inspecting a surface of a target substrate using a multiple-beamlet electron beam column, the automated inspection system comprising:

- an electron source configured to emit electrons;

- a condensor electron lens configured to focus the emitted electrons from the electron source into an illumination beam;

- a beam splitter lens array configured to split the illumination beam to form a primary beamlet array;

- an objective electron lens configured to focus the primary beamlet array onto the surface of the target substrate so as to produce a secondary electron beamlet array;

- a scanning system configured to scan the primary beamlet array over an area of the surface of the target substrate; and

- a detection system configured to detect individual secondary electron beamlets of the secondary electron beamlet array.

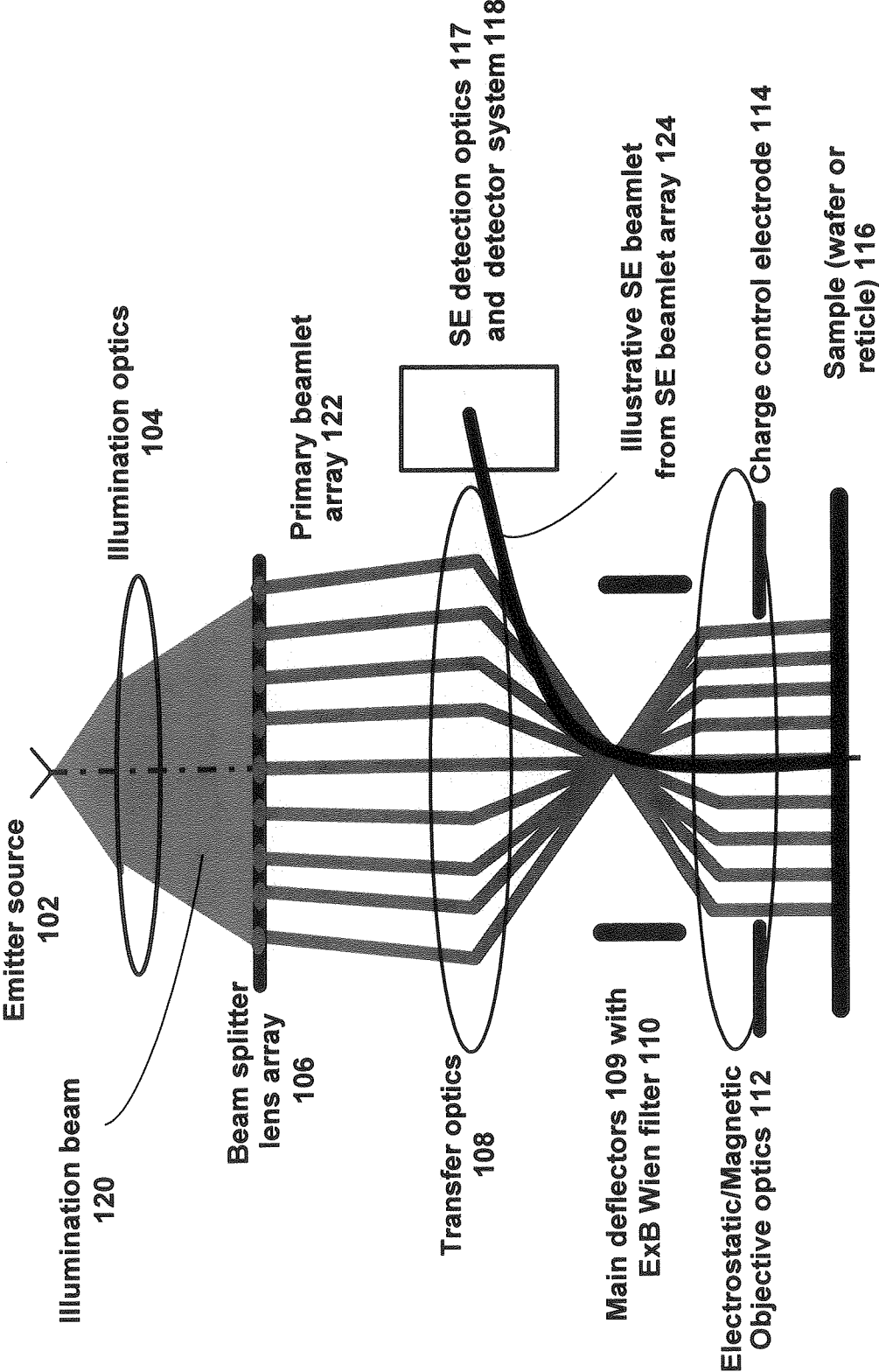


FIG. 1

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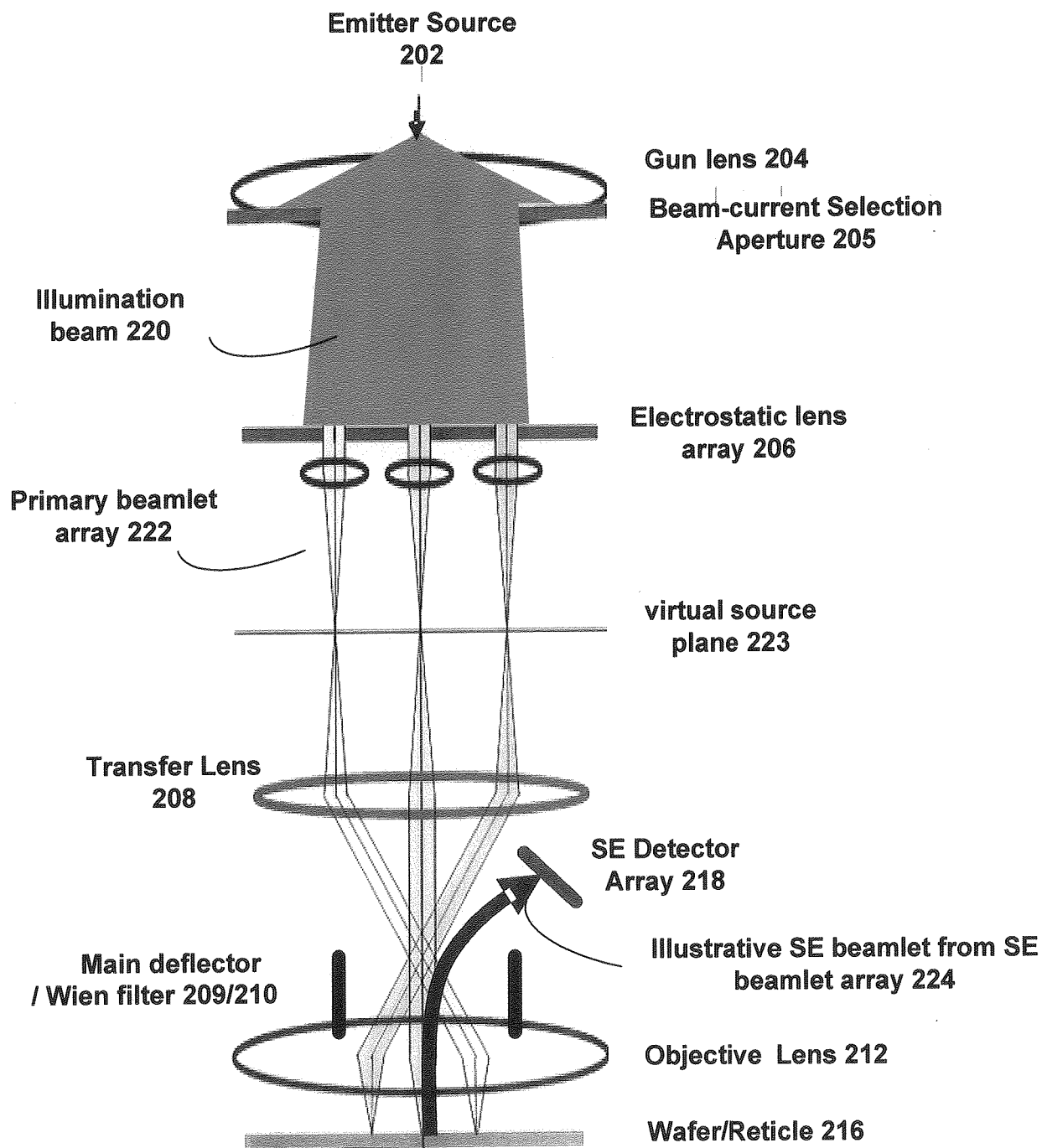


FIG. 2

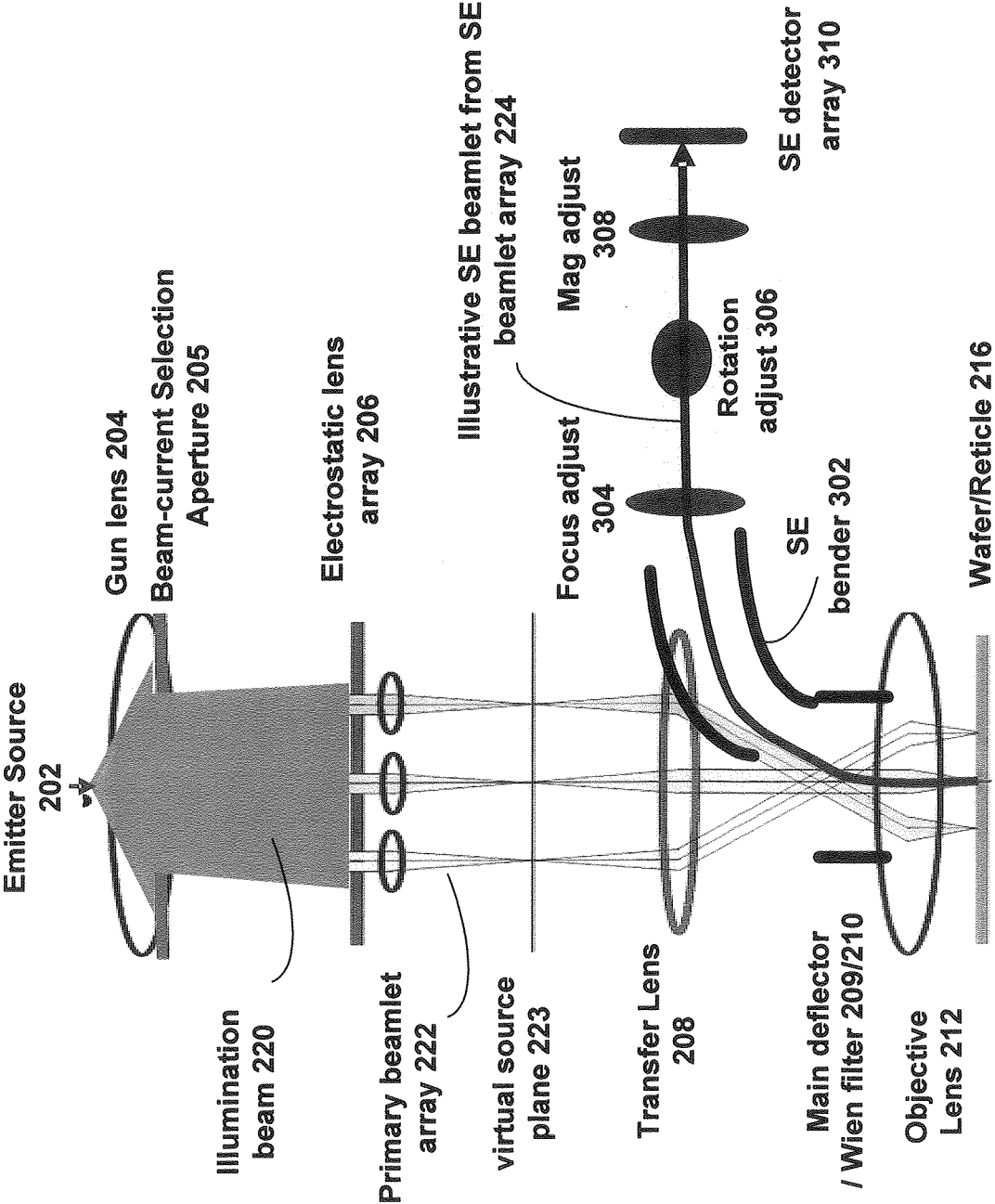
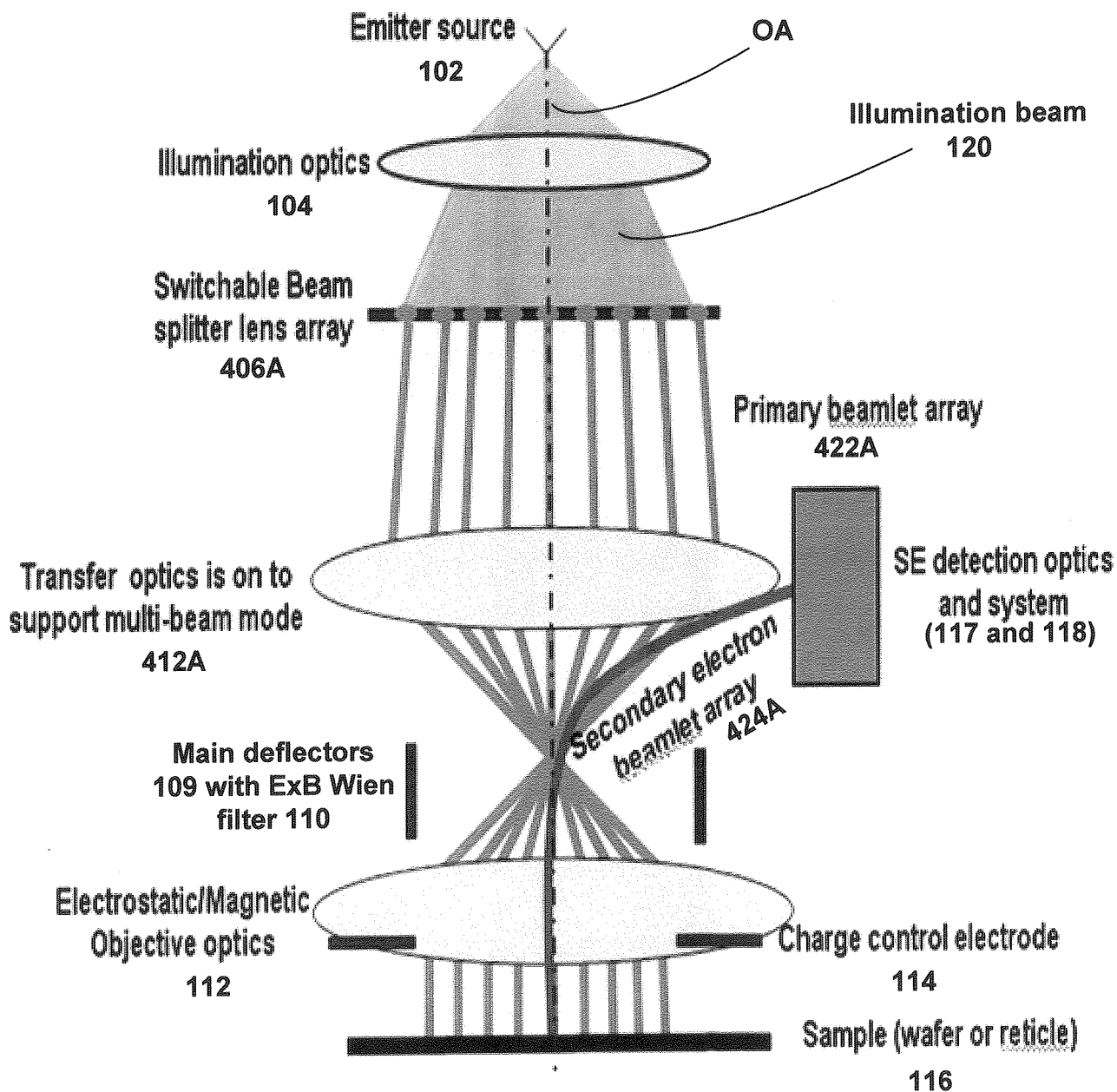


FIG. 3

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**Multi-beam operation mode****400A****FIG. 4A**

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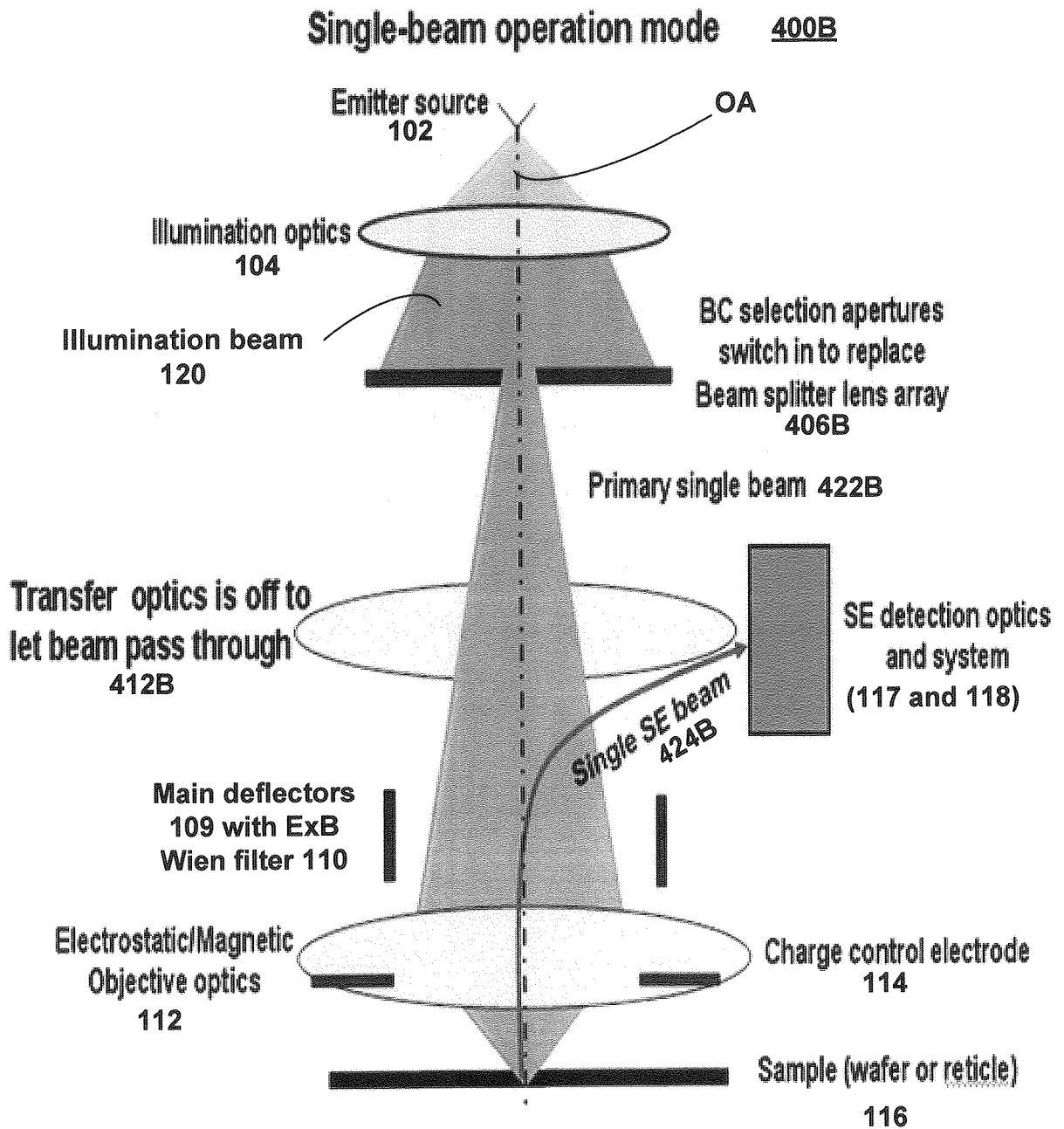


FIG. 4B

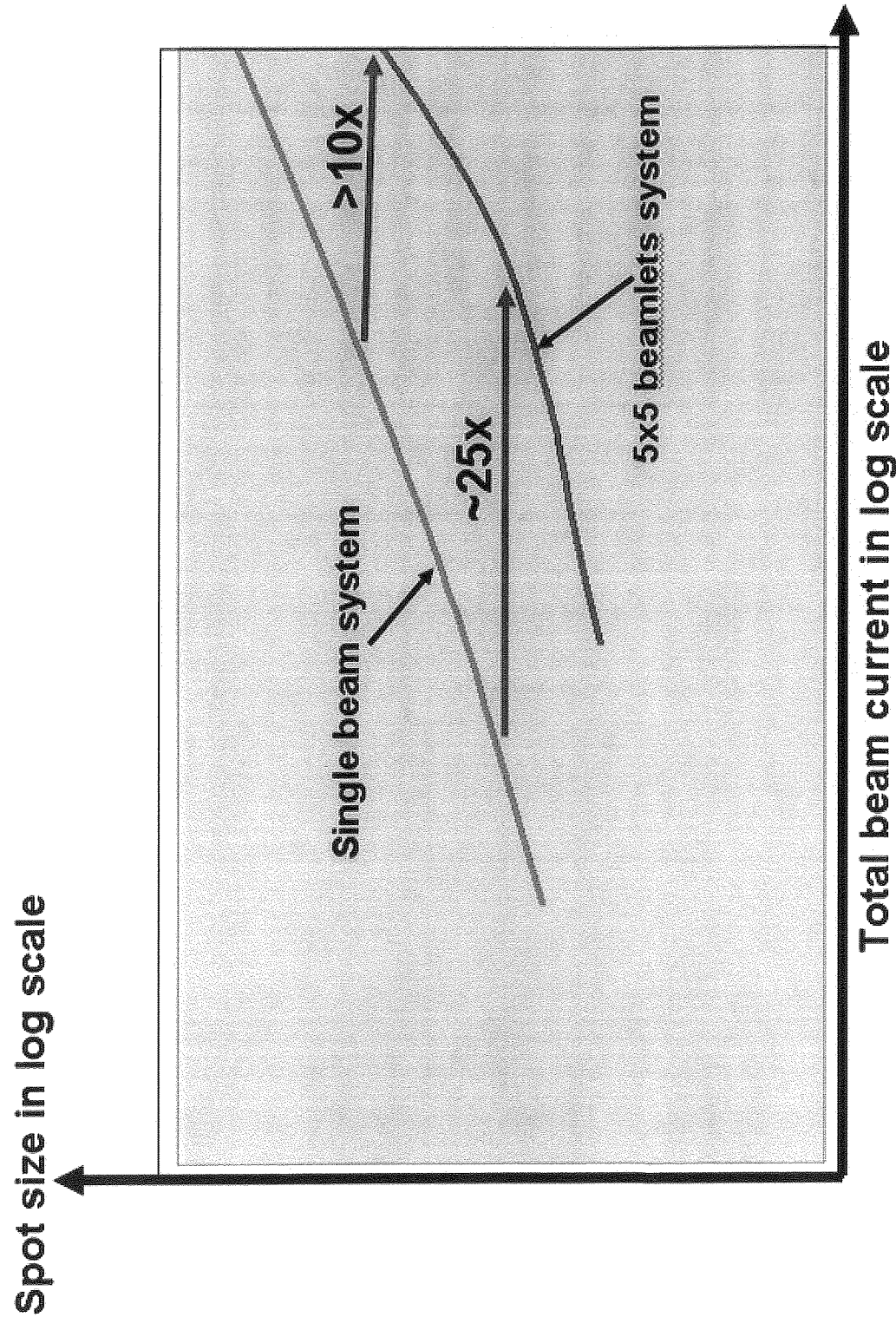


FIG. 5

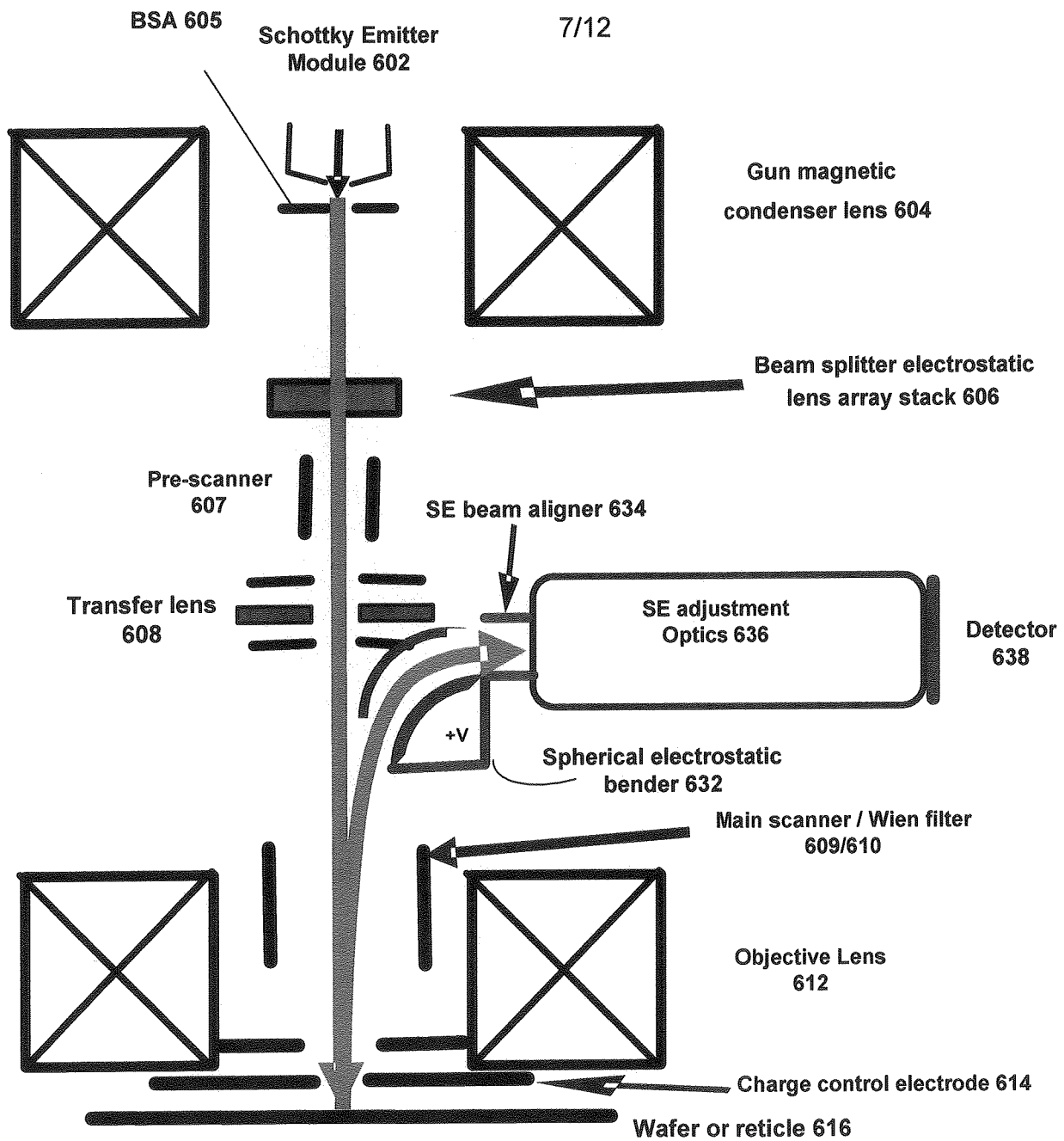


FIG. 6A

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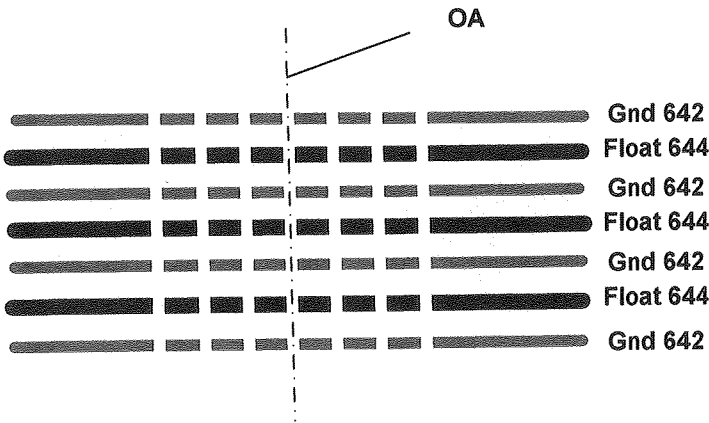


FIG. 6B (Cross-sectional view)

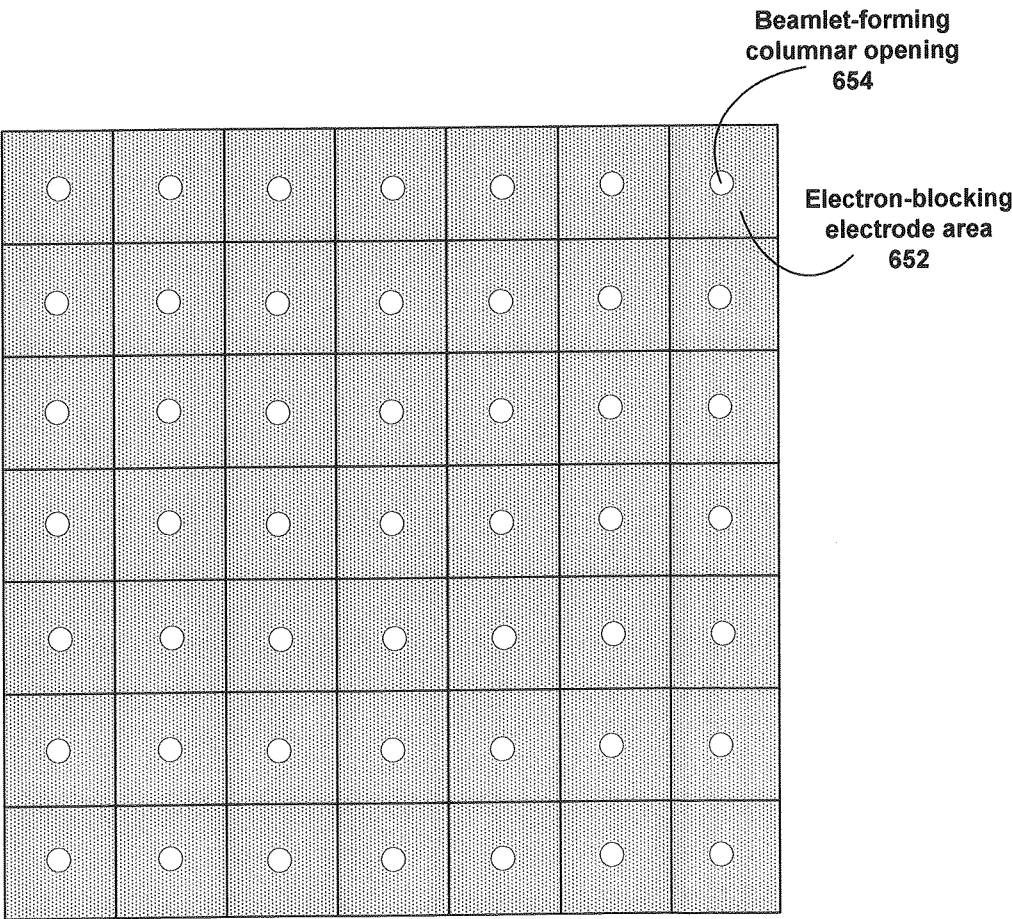


FIG. 6C (Plan View)

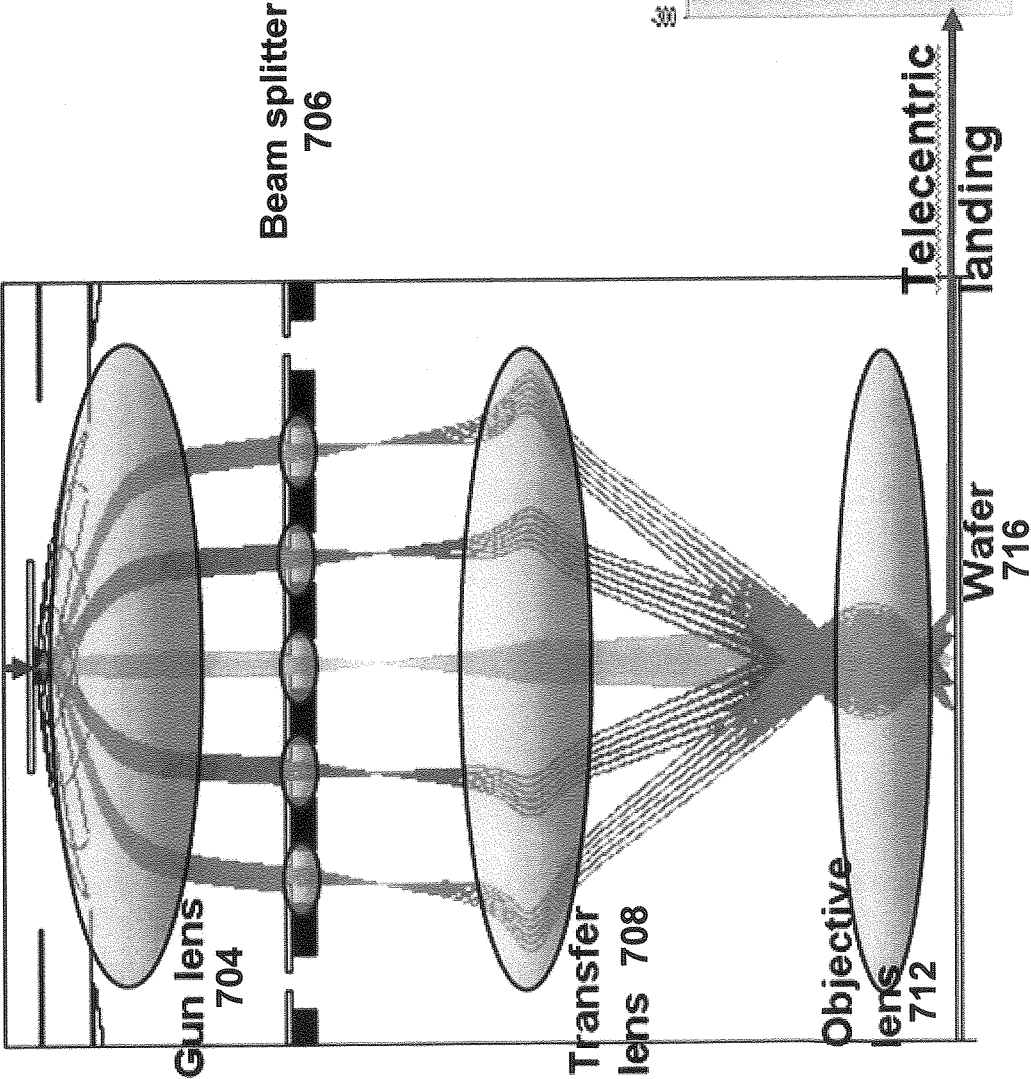


FIG. 7A

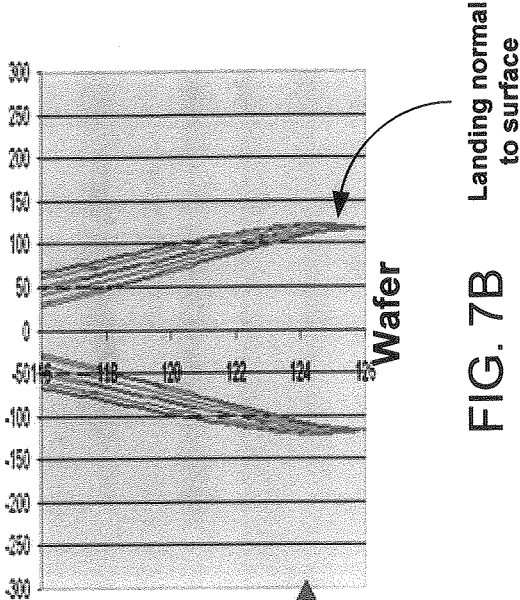


FIG. 7B

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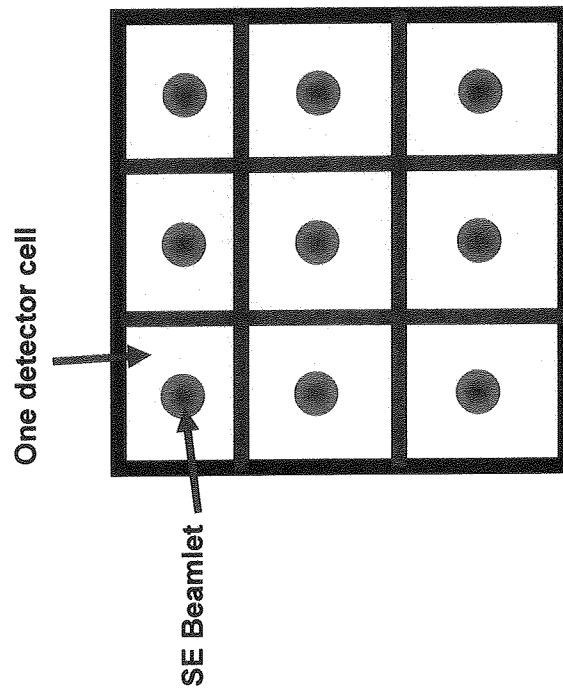


FIG. 8

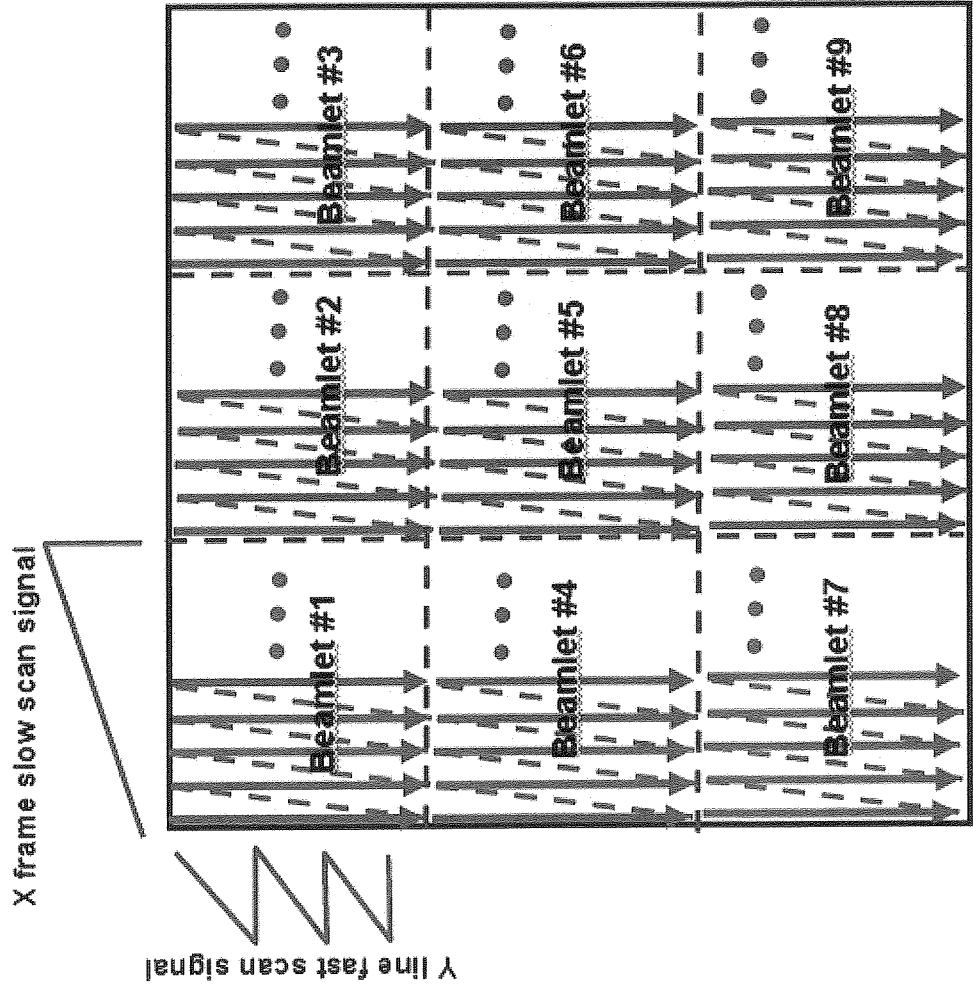


FIG. 9A

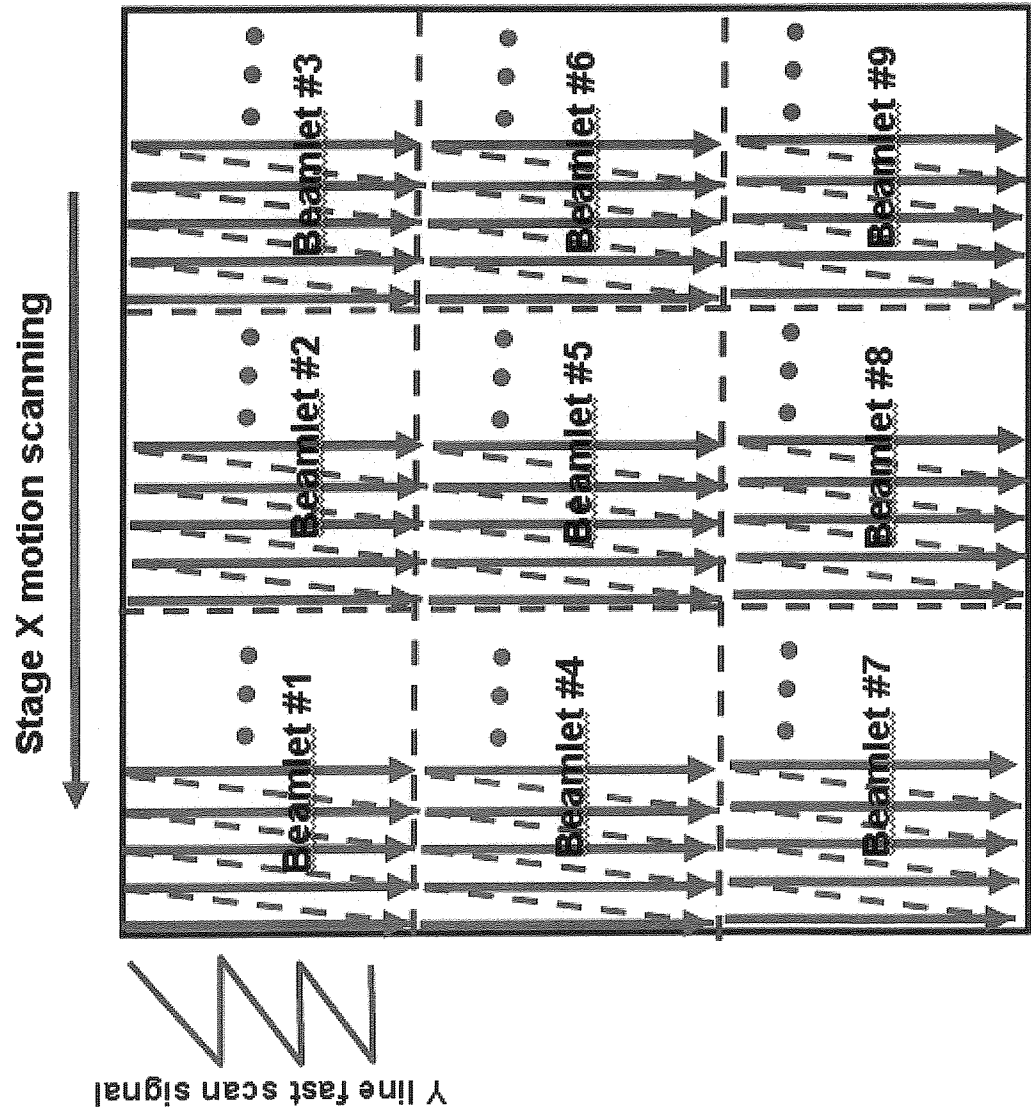


FIG. 9B